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TECHNIQUES FOR SUPERHETERODYNE RECEIVERS ABOVE 100 GIGACYCLES

Final Report

Contract NASw-259

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TECHNIQUES

FOR

SUPERHETERODYNE RECEIVERS

ABOVE 100 GIGACYCLES

Final Report

Contract NASw-259

Edited by

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ABSTRACT

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Techniques are described which are applicable to millimeter wave superheterodyne recievers of the harmonic-mixing, broad intermediate-frequency-band type for use as radiometers. Methods are given for assembling point-contact semiconductor diodes in millimeter waveguides. The progress is reported of a statistically designed experiment to evaluate various whisker and semiconductor materials for use in harmonic generators and mixers. A novel bolometer of ferroelectric material for absolute power measurements at millimeter wavelengths is described and progress in development reported. Experimental results with ferrite Faraday rotators at 2 and 4 mm are given. Design of thermal calibrators for radiometers is discussed. Open resonator techniques are reviewed, and antennas for millimeter radiometers are compared.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

I. INTRODUCTION

The purpose of the research program under Contract NASw-259 was to develop new techniques for superheterodyne receivers in the millimeter and submillimeter wavelength regions. The application of these techniques to radiometers operating above 100 Gc was to be considered. Studies in several specific areas were initiated as called for by the contract. The results are reported in this technical note. Some of the studies are continuing under Contract NASw-662.

The techniques which were studied are described in separate sections. The several studies are related primarily in that they deal with components for superheterodyne receivers specialized for use as radiometers above 100 Gc. The study of ferroelectric bolometers was conducted because of the need for a method of evaluating millimeter wave diode mixers and harmonic generators used in superheterodyne radiometers. Likewise, the thermal calibrator was studied as a necessary auxiliary piece of equipment.

Millimeter wave radiometers are of interest as devices for measuring the radiation of planets, the moon, or other heavenly bodies. Operation at various frequencies would detect any windows or absorption bands in a planet's atmosphere and provide clues to the atmospheric composition. The radiometer might be operated from the earth's surface but ultimately would be carried in a space vehicle so as to eliminate the effects of the earth's atmosphere.

The superheterodyne receiver is of interest to this application because its greater sensitivity permits the detection of smaller temperature differences. Certain techniques which make sensitive superheterodyne radiometers possible at short millimeter wavelengths are the use of harmonic mixing and the use of broad microwave bands as intermediate frequencies. Low noise traveling-wave tube amplifiers serve as IF amplifiers.

II. POINT-CONTACT DIODES

A. Methods for Studying Harmonic Generation and Mixing

Previous work at ECI on harmonic generators and mixers has mainly been done with cross-guide structures. These are operated like the old-time crystal radio. Trial contacts are made between the pointed whisker and semiconductor crystal until an output is obtained. The contact is then broken and trial contacts are made again in a search for a contact giving a better output. It may be necessary to remove and repoint the whisker or to remove and polish the crystal sometime during the process. After much experience, a knowledge is obtained of what output may reasonably be expected from typical junctions of the given material. Then new crystal and whisker materials may be installed in the cross-guide mount and the process repeated. Note that it is impossible to retain any junction for later test and comparison with different junctions unless a second cross-guide mount is built. Frequently, the junction in a cross-guide mount does not have a very long life because of mechanical shock, unnecessary readjustment, and exposure to the atmosphere.

It has been a task of this contract to study new semiconductor materials, new waveguide structures, different whisker configurations, and junction forming methods for the purpose of developing harmonic generators with greater outputs, more sensitive harmonic mixers, and more rugged and stable devices. In order to accomplish this task, a different experimental technique has been devised. The diode junction has been designed as a simple economical part which can be removed from a complete harmonic generator or mixer. A quantity of these simple diodes can be constructed using the different materials and structures. Each in turn can be tested in the harmonic generator or harmonic mixer. Each is available at a later time for retest for comparison or under different conditions. Aging characteristics may be studied. The technique makes practical the study of all the different parameters desired.

A further simplification is now possible. It is not necessary to build a diode for every possible combination of parameters. By use of the random balance statistical technique(1) a limited number of diodes may be constructed and tested to learn the effect of each parameter included in the test. Before the test can be run, definite procedures must be worked out for the assembly of the diodes so that only desired variables will be introduced. The effort devoted to the study of millimeter wave diode devices on this contract has been toward setting up a random balance experiment.

B. <u>In-line Harmonic Generator and Mixer</u>

A simple waveguide diode assembly was designed for evaluation in an in-line structure. Both are illustrated in Figure 1. A one-inch length of RG-99/U waveguide is the basis for the diode structure. The semiconductor die is mounted on the end of the center conductor of a bulkhead-mounting miniature coaxial connector.(2) Silver-epoxy cement(3) has been found to work well for this purpose. The connector mounts in a brass nut soldered to a broad wall of the waveguide with the crystal extending into the waveguide through a drilled hole. The whisker is held in a length of beryllium copper tubing (0.032" O.D., 0.005" I.D.) mounted in the opposite broad wall of the waveguide. This diode assembly has few parts and requires a minimum of machining. It was made for an in-line harmonic generator or mixer. A removable diode assembly could have been designed for a cross-guide device, but it would have been more complex.

The more complicated parts of the harmonic device such as differential drive and tuning adjustment are separated from the diode so that they need be built only once. The differential drive moves the

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(1) T.A. Budne, "Random Balance," <u>Industrial Quality Control</u>, Vol. XV, Nos. 10-11-12; April-May-June, 1959.

(2) Type #31-50, Microdot, Inc., South Pasedena, Calif.

(3) Type #3012, Epoxy Products, Inc., Irvington, N.J.

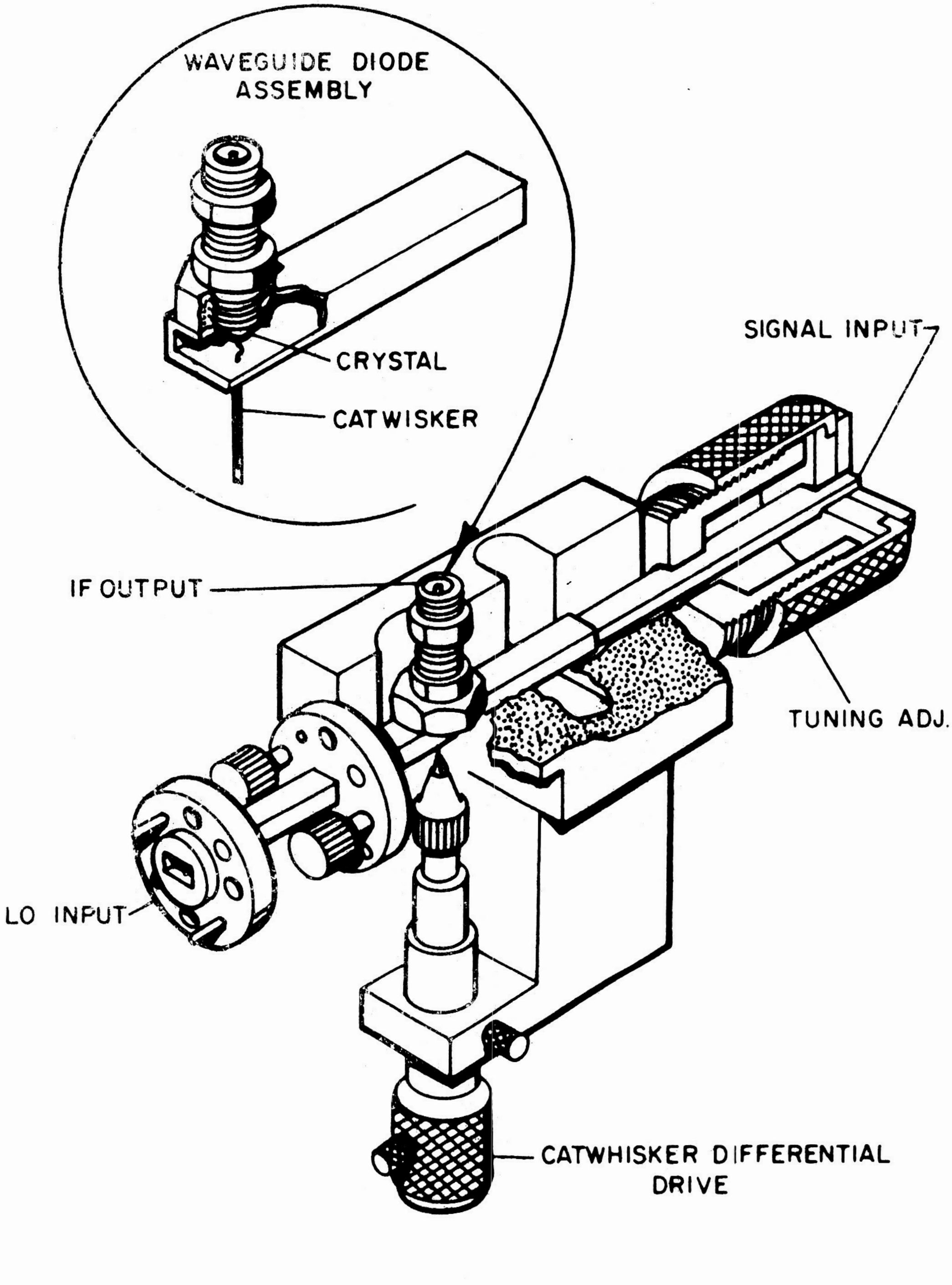

FIG. I - INLINE HARMONIC MIXER FOR DIODE EVALUATION whisker in this device since it is easier to mount the crystal on the coaxial connector. The outside dimensions of the smaller waveguide are reduced so that the guide will slide into the RG-99/U diode mount. Its position is varied as a tuning adjustment.

C. Random Balance Experiment

A variety of crystal and whisker materials have been collected for evaluation. A number of structural arrangements of the diode junction are of interest. To learn the effects of these many variables with a finite number of tests, a random balance experiment[4] has been designed. Statistical methods will be used to analyze the test data. Thirty-six diodes have been assembled for the experiment with each level of each of the following variables occurring an equal number of times:

Variable	No. of Levels
Whisker material and diameter	12
Orientation of whisker bend	2
Crystal material	12
Crystal thickness	2
Penetration of crystal mount into waveguide	3
Diameter of hole through which crystal post passes	2

There are 3456 possible combinations of these variables. By random selection thrity-six diodes can be constructed and tested and the data analyzed to learn the effect of all the variables.

D. Experimental Development

Six waveguide diode assemblies were assembled in order to demonstrate that the in-line harmonic generator would work and to gain experience in the fabrication of the diodes so that techniques could be standardized. Various means of attaching the crystal die to the center post of the coaxial connector were tried. It was found that using 60-40

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(4) Budne, op. cit.

tin-lead solder (liquidus 190°C) caused the center conductor to loosen because of heat effects on the Teflon[5] dielectric of the connector. Using 50-50 indium-tin solder (liquidus 125°C) did not loosen the post. An easier and faster method of attachment than soldering has been found, namely, cementing with a silver-epoxy material. Comparable electrical performance is obtained with the silver-epoxy. The connectors for some of the six diode assemblies had some of the Teflon dielectric cut away to vary the post configuration. This also had the effect of loosening the post. It was concluded that the connector dielectric should not be modified. Some impedance control can be had by varying the diameter of the hole through which the crystal post passes. It was also learned by working with the six preliminary waveguide assemblies that the whisker carrier cannot be soldered in place after the junction is made with any assurance that the junction characteristics will not change. A block with a set screw has been added to the waveguide to hold the whisker carrier without soldering.

These six diodes were tested as second harmonic generators with a 73 Gc fundamental input. Typical outputs of 35 to 42 db above S/N = 1 were obtained. Gallium arsenide dice and tungsten catwhiskers were used. The output was maximized by applying external positive bias. The bias level is not one of the variables assigned at rondom in the experiment. Bias will be adjusted for each diode to the value which gives the greatest harmonic output. When tested as a mixer, the bias will be determined which gives the best overall operation. Measurements have shown that the VSWR looking into the coaxial port varies with the bias. VSWR measurements will be a part of the diode evaluation together with mixer conversion loss measurements.

E. Diode Junction Materials

Twelve different crystal samples have been collected for the experiment from three different manufacturers. Most are gallium

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(5) E.I. du Pont de Nemours and Co., Inc., registered trade-mark for tetrafluorethylene resin.

arsenide; they have a variety of values of bulk properties. Each crystal material has at least three measurable parameters associated with it. These three are the bulk properties: carrier concentration (N), carrier mobility (μ), and electrical resistivity (ρ). For an extrinsic semiconductor such as heavily doped gallium arsenide, $\rho = 1/Ne\mu$ (where e is the electronic charge). Since ρ is uniquely determined by μ and N, it will be eliminated from consideration as a variable. The remaining variables will be combined as μ^2N as a single variable to describe the bulk parameters of the material. The various crystals considered for use in this experiment have values of μ^2N which range from 0.92×10^{23} to 285×10^{23} cm^2/v-sec.

A selection of wires of various materials in sizes from one to seven mils diameter has been obtained from several manufacturers for use as catwhiskers. The materials include phosphor bronze, molybdenum, nickel, platinum-10% ruthenium, stainless steel, titanium, and tungsten. Experiments with soldering techniques for the various wires have been made. The nickel, platinum-10% ruthenium, and phosphor bronze wires were easily soldered with either 60-40 lead-tin solder or pure tin, using rosin as a flux in both cases. Molybdenum, titanium, and tungsten were soldered with the same materials if plated first with a thickness of 0.003" or more of nickel. Stainless steel was soldered easily with Indalloy(6) solder #10 (25% indium - 75% lead) and and Indalloy flux #2. It was found that molybdenum, tungsten, and phosphor bronze can be pointed by electrolytic etching. Pointing by grinding using alcohol as a lubricant may be used for titanium and any other metals which cannot be electrolytically etched.

F. Junction Forming

Methods have been studied for electrically forming or welding point-contact junctions. The object was to establish the optimum conditions, if any, under which the diode junctions can be strengthened

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(6) Indium Corp. of America, Utica, N.Y.

mechanically and stabilized electrically while retaining other desirable electrical properties. Variations in junction forming methods were not included in plans for the random balance experiment because they are not truly independent variables. A particular forming method useful for one crystal material may have no effect at all on another material. Therefore, some preliminary experiments have been performed to determine suitable, standardized methods to use with each diode material. Further improvements can be studied after the random balance experiment has indicated the more promising materials from an electrical standpoint.

The investigation of electrical forming was started with measurements of junction tensile strength under various conditions. Junctions were formed without any mount. Two micromanipulators positioned the catwhisker in a vertical position above and in contact with the crystal. The catwhisker was soldered to a calibrated deflection beam used to measure the contact force and tensile strength. The capacitor discharge circuit of Figure 2 was used to pulse the junctions in the reverse direction while the low frequency rectification characteristics were viewed on a V-I curve-tracing oscilloscope. Although it is not believed that a correlation exists between the V-I curves and the microwave properties, the curves do indicate when successive pulses are furnishing sufficient energy to affect the junction. With this setup it was found by measurement of gallium-arsenide phosphor-bronze junctions that the tensile strength of the weld depends in part on the contact force applied during forming. Junctions were made both with polished crystals and with polished and then etched crystals. Neither condition was consistently better than the other.

The microwave characteristics of some point-contact junctions were studied as a function of forming. Forming was done with reverse bias in the same manner as was used for the tests of tensile strength. Junctions were tested as second harmonic generators with a 73 Gc fundamental. The in-line mount with removable waveguide section

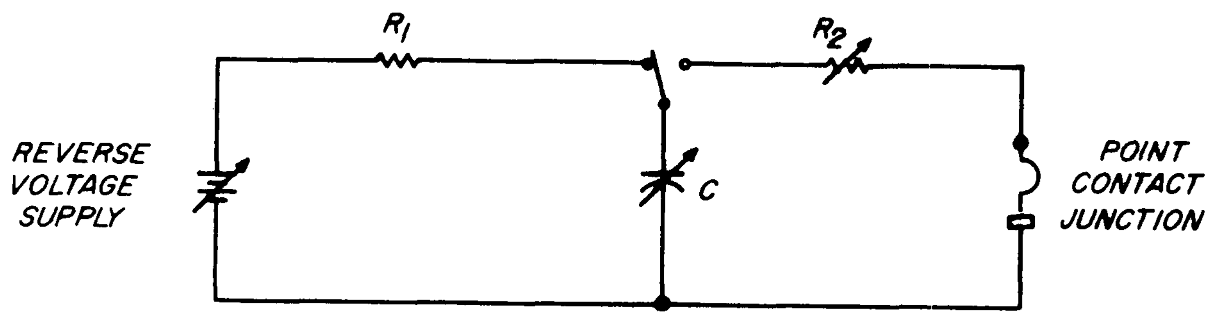

FIG. 2 —CIRCUIT FOR CAPACITOR DISCHARGE FORMING OF POINT CONTACT DIODES

was used. These limited tests showed that forming with reverse bias (-25 volts from a 0.25 μf capacitor through a 500 ohm resistor) does not improve or stabilize the microwave performance of gallium arsenide diode junctions. Small amounts of forward bias and self bias from applied RF power does give stable welded junctions. Reverse bias less than -25 volts has not yet been tested. Forming pulses applied to silicon diode junctions had no effect at all. These tests led to the conclusion that a single junction forming method cannot be used with all the diodes in the random balance experiment. Forming voltage will be applied to the diodes to the extent necessary to obtain harmonic generation.

G. Test Methods

Each diode is formed while RF power at 4 millimeter wavelengths is applied. Second harmonic output is monitored with a point-contact diode detector in the appropriate waveguide size. After further development the ferroelectric bolometer will be used to measure harmonic output with greater absolute accuracy. The fundamental frequency power level may also be measured with the ferroelectric bolometer. At present, it is measured with a thermistor. Harmonic generation efficiency as a function of input power level will be measured within the limitations of the power available. Each diode will also be tested for the third harmonic output by using a smaller waveguide output which will cut off the second harmonic. Selective tests may be made of higher order harmonics where sufficient output exists to be detected.

The diodes will also be tested as harmonic mixers utilizing the same in-line structure. The signal will come from a harmonic generator driven by a 4 mm klystron. The local oscillator will be a second klystron adjusted to produce a center intermediate frequency of 3 Gc. The intermediate frequency amplifier has a bandwidth of about 2 Gc centered at 3 Gc. The components of the IF amplifier section have been obtained. They consist of a low noise traveling-wave tube for the first stage and a higher gain TWT for the second stage. The low noise

TWT is a Watkins Johnson type WJ-211, solenoid operated. A power supply has been designed and built to drive the solenoid and TWT. These are shown in Figure 3. The second atage is a Hewlett-Packard model 490B traveling wave tube amplifier.

The mixer tests are planned for a high intermediate frequency and a broad IF bandwidth because these characterize the mixers in millimeter radiometers of advanced design. Performance of millimeter wave radiometers using mixers of this type has been reported elsewhere[7] and is summarized in Section VII. The tests are designed to provide general design data for harmonic mixers. Conversion loss and noise ratio will be measured as a function of local oscillator power and biasing for second and third harmonics. Comparative data for IF bandwidths of 30 to 100 Mc centered at frequencies between 100 and 200 Mc will be measured. An IF amplifier with several different bandpass filters is available for this purpose. The VSWR looking in the coaxial IF port of the mixer will be measured over the IF band as an aid to relative evaluation of the diodes in their different configurations. The ferroelectric bolometer will be used in mixer tests if available. Its development was motivated largely by the need for means of measuring accurately the low-level signal power into a mixer for 2 mm wavelengths and less.

Some tests of conventional mixing will be made at 2 mm if sufficient power can be obtained from a harmonic generator to serve as a local oscillator. In any event performance of harmonic mixing versus harmonic generation and direct mixing for the same fundamental source power can be made.

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(7) M. Cohn, F.L. Wentworth, J.C. Wiltse, "High sensitivity 100 to 300 Gc radiometers," to be published in Proc. IEEE.

Figure 3 - Low Noise TWT and Power Supply

III. FERRITE MODULATOR

A. Requirement

Periodic connection to a thermal reference source is necessary to the operation of a Dicke-type Radiometer. The conventional rotating eccentric resistance card is difficult to utilize with small waveguide such as RG-136/U, used for the band 110 to 170 Gc. In addition the rotation rate needed for a 1 kc modulation would be prohibitive. It would be advantageous to devise an electronically-operated device to be used instead of a mechanical one. Y-circulators (which can be used as modulators) have failed to have the required bandwidth, which should approach 8 Gc. A device using the principle of Faraday rotation was chosen for development for this purpose.

B. Theory of Operation

The phenomenon of Faraday rotation of the polarization of an electromagnetic wave passing through a ferrite material in a steady state magnetic field can be utilized to switch the radiometer input electronically between its antenna and a dummy load. In the usual configuration a ferrite rod is placed in a short section of circular waveguide so that their axes coincide. Transitions to rectangular waveguide are made at each end of the circular waveguide. A solenoid wound around the section containing the ferrite supplies the axial magnetic field needed to give a desired amount of Faraday rotation. With no current in the solenoid, the antenna signals pass through the ferrite to the receiver. With current in the solenoid, a magnetic field exists in the ferrite and the polarization of the antenna signals is rotated. If the current is such as to give 90° of rotation, the signals will propagate through the ferrite but be reflected at the rectangular waveguide which is beyond cutoff for this polarization.

Looking toward the antenna the receiver sees, in effect, a dummy load consisting of the ferrite, a waveguide beyond cutoff, and a suitably oriented resistance card. By controlling the temperature of these parts, they become a thermal reference element which can be switched in and out by electronic control of the solenoid current.

The desired characteristics of the modulator are as follows:

(1) It should introduce very little attenuation (≤ 1.0 db) in the path from the antenna to the mixer so as to minimize the degradation of the radiometer thermal sensitivity.

(2) On the alternate part of the modulation cycle the isolation or attenuation between the antenna and mixer should be sufficient to reduce the power from the antenna to a small percentage of its unattenuated value. Twenty db of attenuation should be sufficient (some additional fixed attenuation of known value may have to be inserted when viewing the sun.)

(3) In order that LO power reflected from the mixer not be again reflected back to the mixer and appear as a chopped signal, which would modulate the crystal impedance, it is necessary that the modulator present nearly equal and preferably low VSWR's to the mixer during both portions of the modulation cycle.

(4) The bandwidth of the modulator must be large enough to provide modulating action for the broadband receiver passbands on each side of the LO frequency.

Commercially available ferrite devices will marginally satisfy all of the requirements except that of bandwidth (4). Some improvement in insertion loss (1) and VSWR (3) would be desirable. Barnes has shown that broadband ferrite devices employing Faraday rotation can be built at millimeter wavelengths.[(8),(9)]

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(8) C.E. Barnes, "Broad-band isolators and variable attenuators for millimeter wavelengths," IRE Trans. on Microwave Theory and Techniques, Vol. MTT-9, pp. 519-523; November, 1961.

(9) C.E. Barnes, "Further developments in dielectric waveguide devices for millimeter wavelengths," presented at the 1962 PGMTT National Symposium, National Bureau of Standards, Boulder, Colorado; May 22-24, 1962.

C. Development of Faraday Rotator

The preliminary development of a ferrite Faraday rotator using RG-136/U waveguide was carried out in an effort to obtain a device which would give an insertion loss of 1 db or less at 0° rotation and 20 db or more at 90° rotation for frequencies near 140 Gc. A rotator was built using the nickel-zinc ferrite, TT2-111,[10] as a section of dielectric waveguide. The theory of operation of such a structure has been given in the article by Barnes;[11] however, his measurements have been made at frequencies below 60 Gc.

D. Preliminary Results

The device was assembled in the manner illustrated in Figure 4. The ferrite was machined into a solid cylinder 0.500" long by 0.031" diameter. A tapered matching section of Stycast[12] K-10, 0.062" by 0.031" diameter, was placed at each end of the ferrite. The rotator was assembled so that the ferrite was positioned between open ends of the waveguide and the Stycast protruded into the waveguide. A coil was wound around a form made of a non-metallic material, namely a carbon impregnated phenolic. The ferrite rod was placed concentrically within the coil form. The measured results for this particular loading of ferrite and Stycast with a 256 turn coil are as follows:

Coil Current	VSWR	Insertion Loss
0 ma	1.35	8.5 db
58	1.30	27

Other ferrite materials such as 5E1,[13] TT414,[14] and TT390[14] were tried. All of these materials had very low activity with not much

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(10) A product of Trans-Tech, Rockville , Md.

(11) See the reference in footnote number 8.

(12) Emerson and Cuming, Inc., Canton, Mass., registered trademark for casting resins.

(13) A product of Ferroxcube Corporation of America, Saugerties, N.Y.

(14) Trans-Tech.

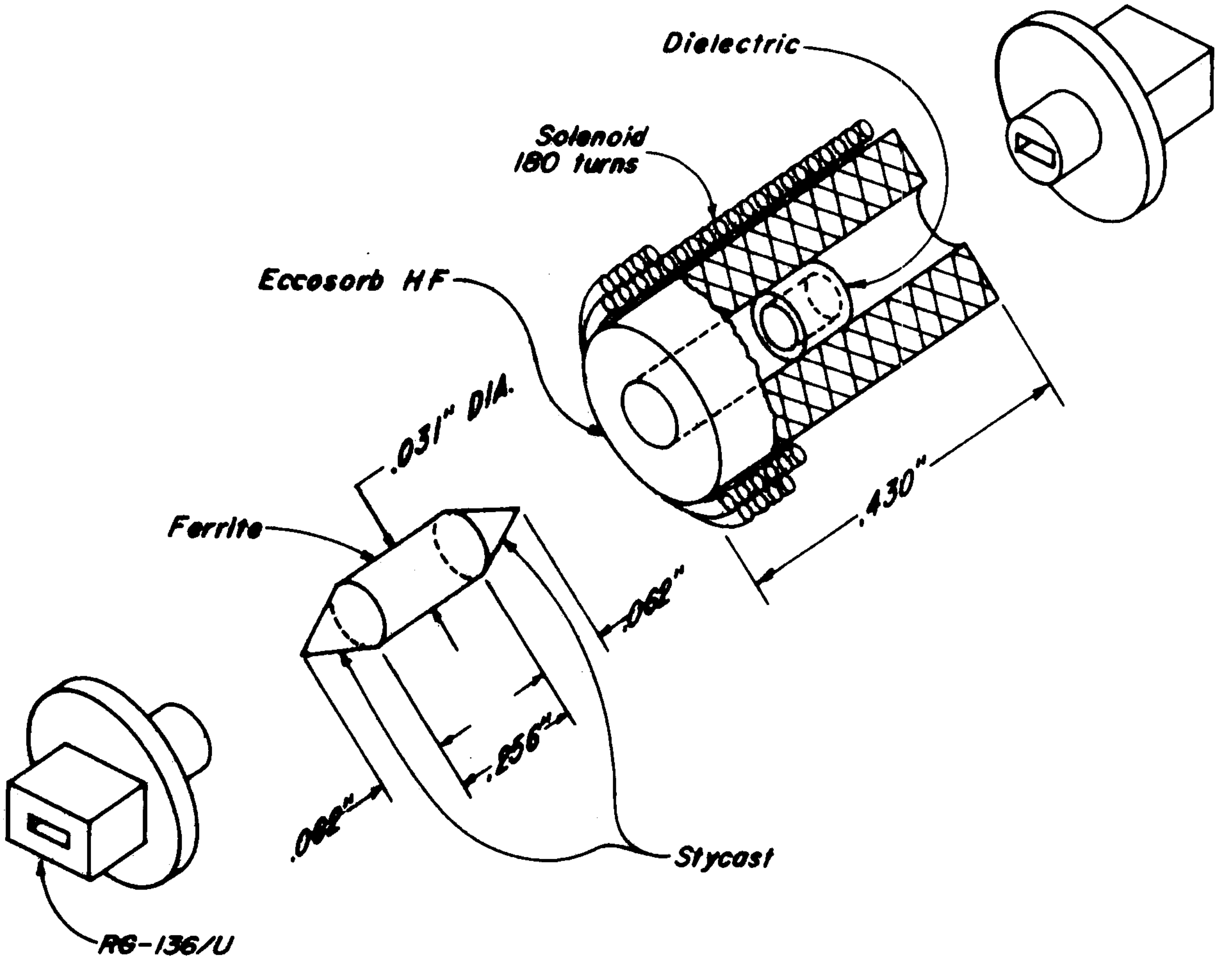

FIG. 4 – FERRITE MODULATOR CONSTRUCTION

improvement in insertion loss. Although little is known of the loss tangent of Stycast at 2 millimeter wavelengths it was suspected that the Stycast was rather lossy and thus contributed the greater portion of the 8.5 db insertion loss. The next step was to eliminate the Stycast from the launching scheme.

Since the ferrite modulator is a surface wave structure, it is difficult to determine if the minimum observed insertion loss is due to dissipation or whether it includes surface wave launching and collecting losses as well. A prior analysis[15] has shown that the desired dipole mode (HE_{11}) can be efficiently launched onto and collected from a dielectric rod by a properly placed and energized annular slot which is concentric with the rod axis. The configuration shown in Figure 5 was tried with annular slots of 0.004" and 0.007" gap. The insertion loss varied from 24 db to greater than 40 db as a function of magnetic field. It is believed that the large values of insertion loss are due to a large mismatch caused by the annular slots at each end of the ferrite rod.

Launching the surface wave with a tapered transition has the advantage of providing a reasonably good match; therefore, this method was used again in a different manner. It was decided to make the tapers out of the ferrite itself, thus making the tapers and solid cylinder all one piece.

Measurements were taken at 156 Gc of the one-piece tapered ferrite rotator. The results of the measurements are shown in Figure 6 and 7. The rotator and associated harmonic generator, detector, and other components used to test it are shown in Figure 8.

In order to obtain broadband operation of a ferrite modulator which operates on the principle of Faraday rotation, the ferrite

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(15) M. Cohn and M. J. King, "Selected Surface Wave Excitation Studies," Electronic Communications, Inc., ASTIA Document 275 438; March, 1962.

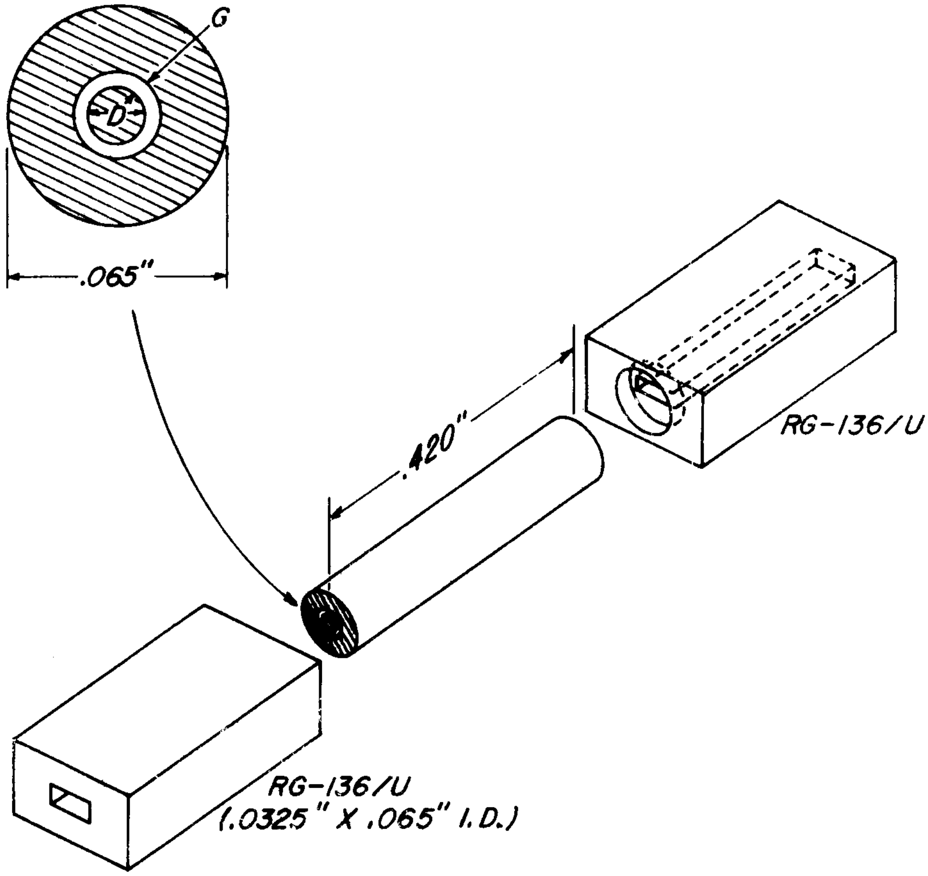

FIG. 5 – FERRITE MODULATOR UTILIZING ANNULAR SLOT LAUNCHING

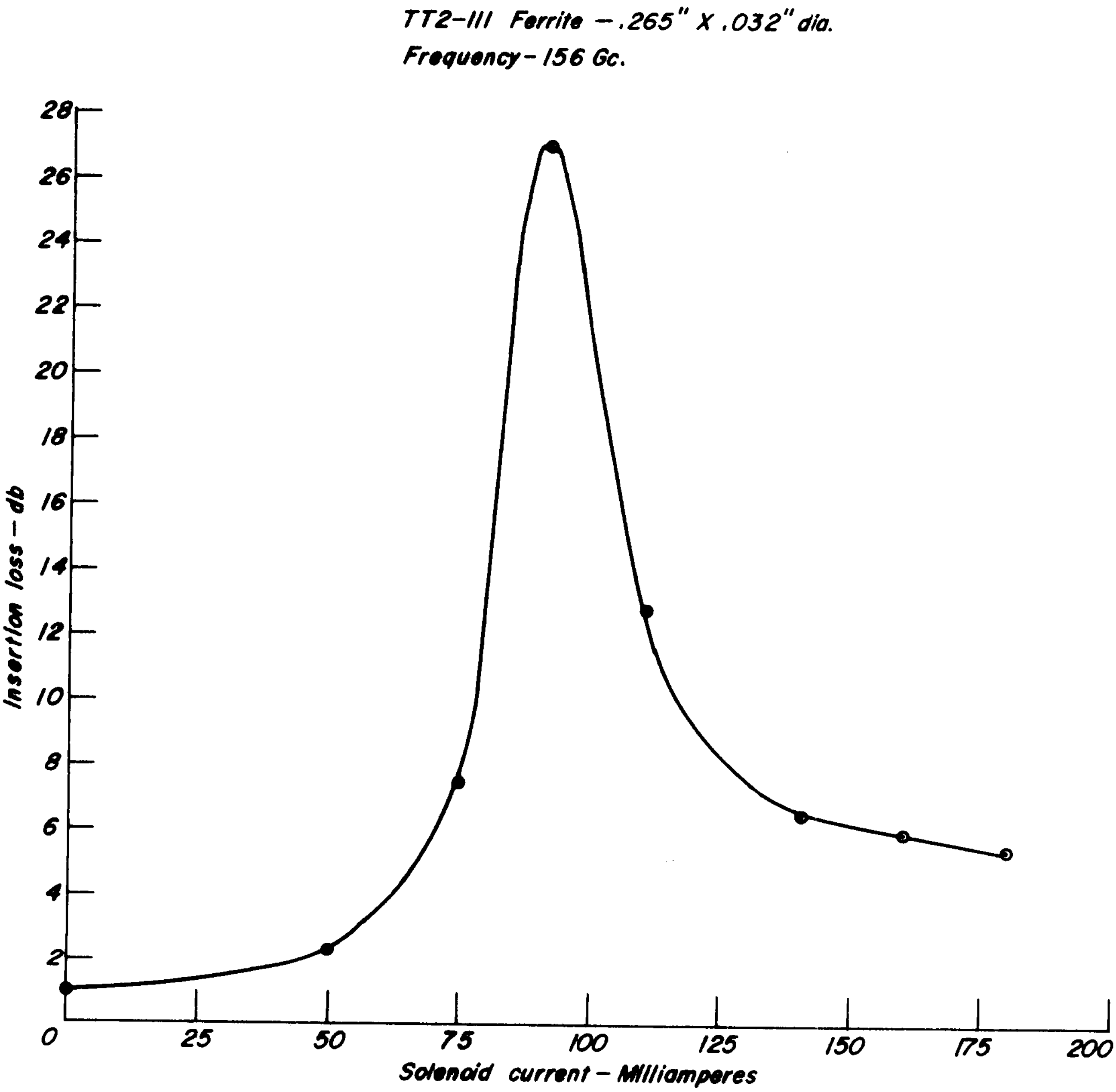

FIG. 6 — FERRITE MODULATOR PERFORMANCE AT 2mm

TT2-III FERRITE

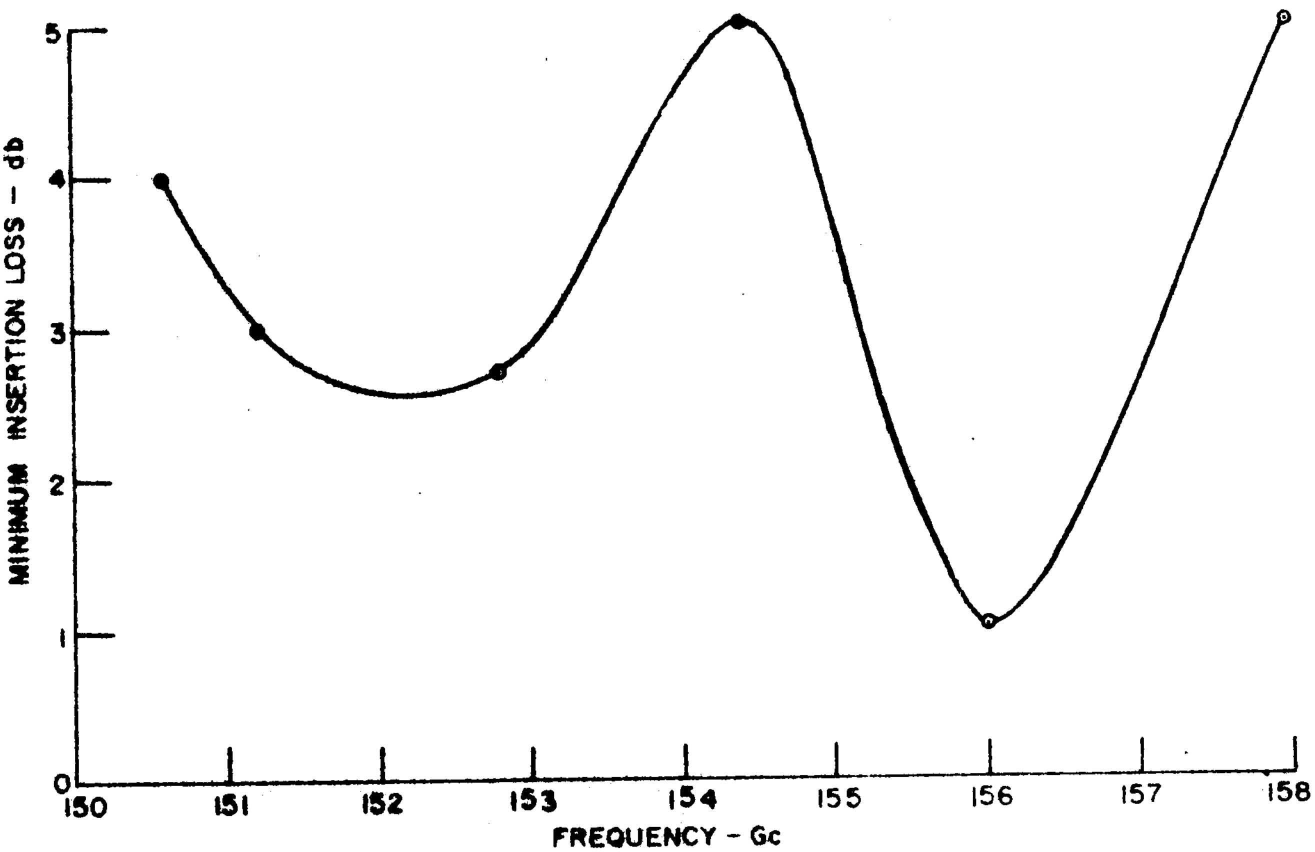

FIG. 7 - MINIMUM INSERTION LOSS vs FREQUENCY

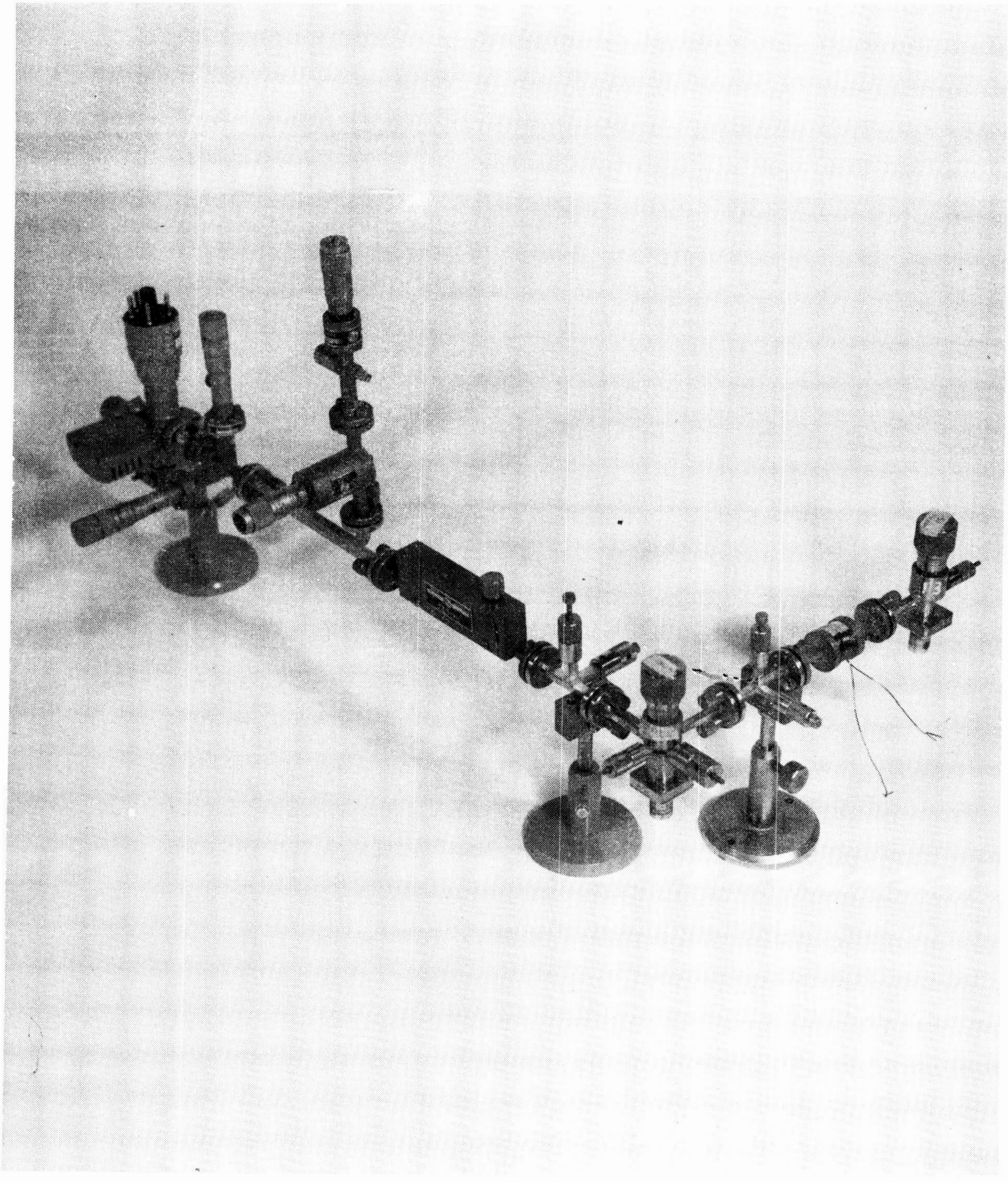

Figure 8 - Faraday Rotator and Test Setup at 2 mm

rod must act as a dielectric waveguide with no conducting walls surrounding it.[16] The data in Figure 7 shows a sharp increase in the minimum insertion loss from 1 db to 5 db at frequencies 2 Gc above and below 156 Gc which would limit the rotator's use to narrow band applications. The narrow bandwidth is believed to be caused by the protrusion of the conical tapers of the ferrite rod into the guide 0.062" on each end. Half of the ferrite is within the waveguide walls and half is outside the waveguide walls. The part of the structure which has the ferrite within the guide walls acts as a conventional Faraday rotator, and hence is narrow banded. It was therefore concluded that dielectric tapers, rather than ferrite must be used.

E. Further Modifications

Another ferrite rotator was designed such that an investigation might be carried out at 70 Gc (where measurements would be easier) to determine the material most suited for use as tapered transitions from the standard waveguide to the dielectric waveguide. Most of this work was supported by ECI company funds. In order to keep the insertion loss as low as possible a material must be selected that has a low loss tangent at millimeter wavelengths. Several samples from different manufacturers have been tried; however, the one which is most promising is Lucalox,[17] a high purity alumina. An isolation of 23.8 db or greater and an insertion loss of 1 db or less has been measured over the frequency range from 70 to 72 Gc. The results of these measurements are shown in Figure 9. Although the bandwidth is 2 Gc instead of the required 8 Gc, it is believed that the bandwidth may be increased by further modification of the taper structures. These tests will be performed on Contract NASw-662. It is hoped that from the techniques used at 70 Gc a ferrite rotator at 140 Gc with a bandwidth of 8 Gc will evolve.

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(16) See the reference in footnote number 8.

(17) General Electric Co. registered trade-mark.

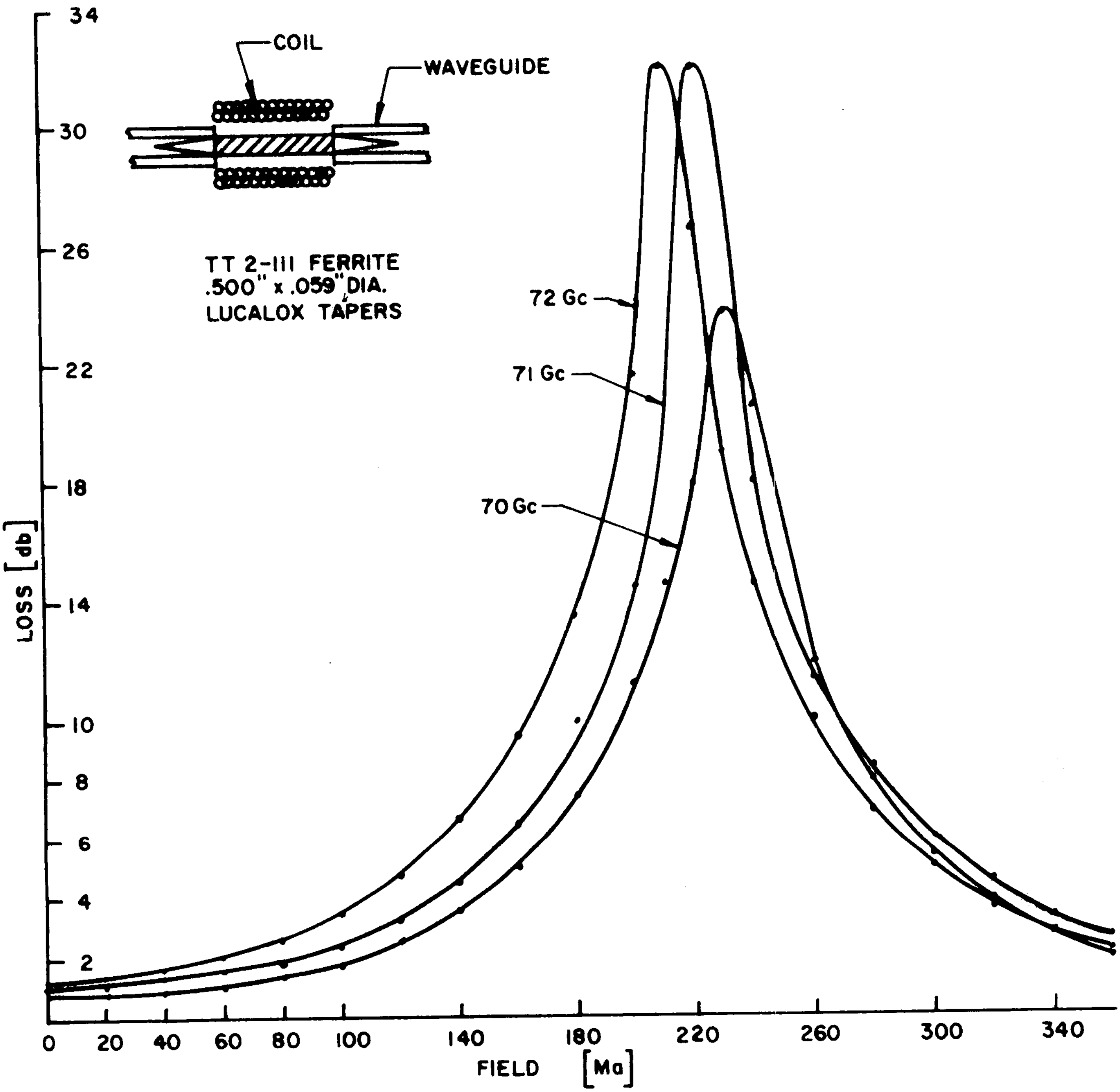

FIG. 9 - FERRITE MODULATOR PERFORMANCE AT 4 MM

IV. THERMAL CALIBRATOR

A. Introduction

In order to calibrate millimeter wave radiometers a self-contained unit is needed which, when placed in front of the radiometer antenna, will radiate millimeter wave energy from a source of known temperature. Then the radiometer output, such as a deflection on an oscillograph, can be calibrated in terms of temperature difference from the chopper blade temperature for fixed conditions of mixer operation, IF amplifier gain, and audio gain. By adjusting the temperature of the calibrator close to the temperature of the reference source in the radiometers, the sensitivity of the radiometer to a minimum temperature change can be measured.

Design studies on thermal calibrators for millimeter wave radiometers were conducted under this contract. A type of construction and suitable materials were specified. This information was used to build a thermal calibrator on Contract DA36-034-ORD-3509RD with the Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland. The experience gained in the construction and checkout of the calibrator has been used as a basis for recommendations for future designs. The work on the thermal calibrator task is described below.

B. Requirements

The requirements on the calibrator are that:

1) It be highly emissive at the millimeter wave frequency of operation,

2) it be heated evenly over its radiating surface to the desired temperature,

3) it be large enough to subtend the main beam of the radiometer antenna at the distance used.

The reference source of a millimeter wave laboratory radiometer is conveniently adjusted by heaters to a temperature somewhat above ambient, say 30° to $40^{\circ}C$. The thermal calibroator then should be adjustable in temperature from 30° to $100^{\circ}C$ or more so that it may be used for initial set-up of radiometer and for later sensitivity measurement. The thermal calibrator must have an emitting cross-section at least 21 inches in diameter in order to subtend a 1/3 degree main beam at one Rayleigh distance (D^2/λ) from a 140 Gc radiometer antenna.

C. Calibrator Development

A good emitter is necessarily a good absorber and a poor reflector. A number of high temperature microwave absorbers were tested for reflectivity and absorption at 234 Gc with the following results:

Material	Relative Level of Reflected Signal	Relative Level of Transmitted Signal
Eccosorb[18] AN-72	-21 db	-35 db
B.F. Goodrich Sponge Products[19] Type G	-26	-28
McMillan Industrial Corp.[20] HBL-2CT	-28	-35

The McMillan HBL-2CT absorber, illustrated in Figure 10, was selected for use.

The design problem reduces to building a unit having a 21-inch diameter surface of McMillan HBL-2CT which can be heated evenly to temperatures between 30° and $100^{\circ}C$ or more. The unit which was built to do this consists of an oven with a 21" square window behind which the emitting surface is mounted. The window consists of two 3/4 mil Mylar[21] sheets separated by 1/2" dead air space in order to reduce conducted heat losses from the oven. Johns-Manville Marinite-36, an

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(18) Emerson and Cuming, Inc., registered trade-mark for microwave absorbers.

(19) Shelton, Conn.

(20) Ipswich, Mass.

(21) E.I. DuPont de Nemours and Co., Inc., registered trade-mark for polyester film.

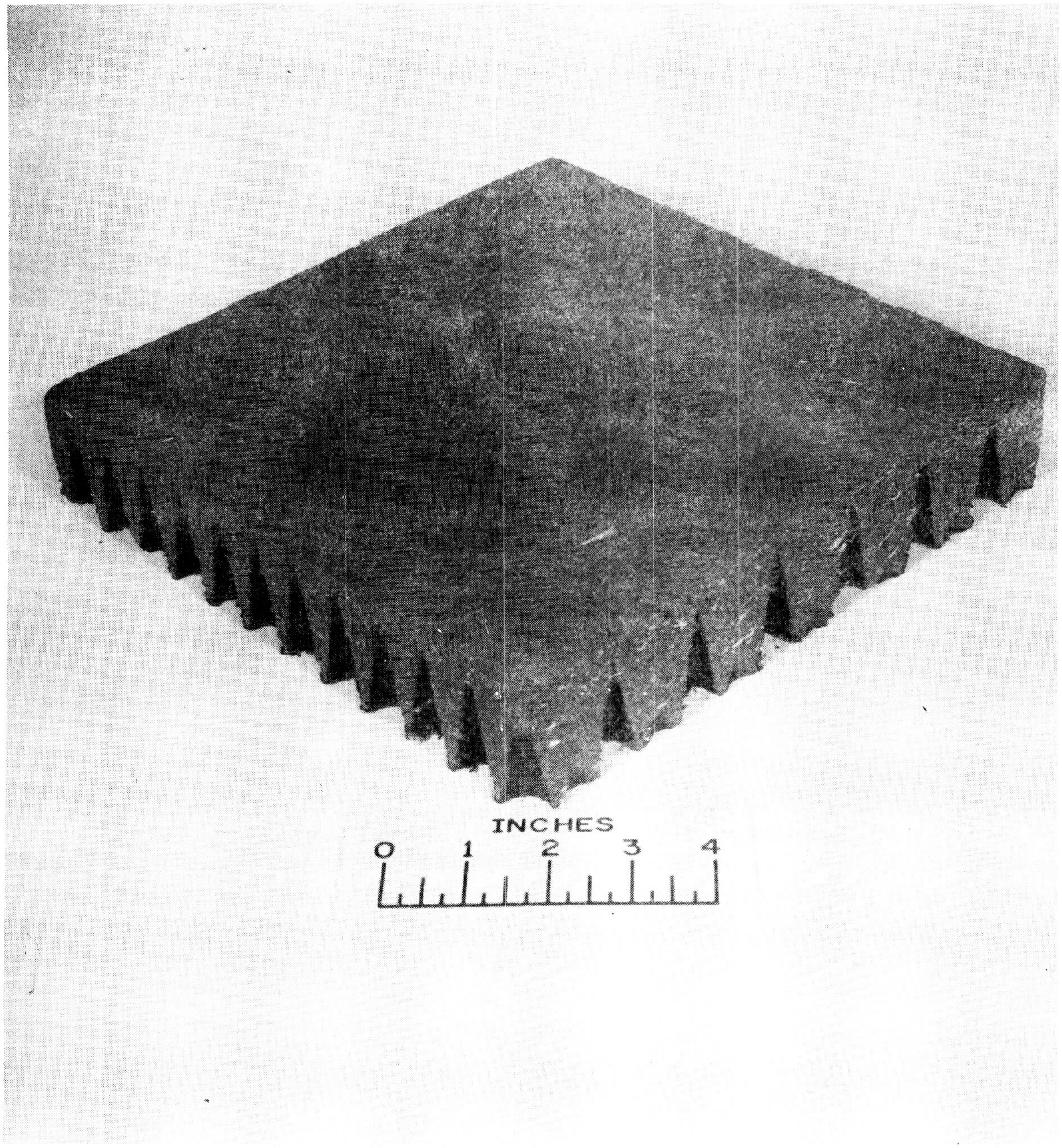

Figure 10 - Millimeter Wave Absorber/Emitter

insulating sheet material, is used for the walls of the oven which are held together at all edges with angle stainless steel. The emitting surface is 24" square and is mounted 2" back of the window with free air space at all edges and in back. The emitter is heated by circulating the air in the oven over three 725 watt electric heating elements mounted behind the HBL-2CT material. An 80 CFM centrifugal blower does this.

D. Performance

After the thermal calibrator was completed, tests were made to determine how evenly the emitter was heated over its surface. Nine thermocouples were imbedded at various places in the back of the emitter to within 1/16" of the front surface. With full voltage on the heaters and the blower on, the temperature readings varied from 180° to 210°C. However, a thermocouple stuck through the Mylar window into the front surface of the emitter gave a reading of about 160°C. Apparently thermocouples imbedded from the rear gave erroneously high readings because the wires in the space near the heaters conduct heat to the junction. The nine thermocouples were then placed through the window and imbedded in the front of the emitter on a square grid of unit size 5-1/2 inches. Baffles were placed in the oven by trial and error until the air flow was redirected so as to heat the emitter evenly. This reduced the temperature at the nine thermocouples to $130^{\circ} \pm 7^{\circ}$C. If the heater power is reduced the variation is less, typical values being $113^{\circ} \pm 4.5^{\circ}$C and $93^{\circ} \pm 3.5^{\circ}$C.

E. Analysis

A thermal calibrator of the type just described is useful with narrow beam radiometers whose reference temperature ranges from near ambient to several hundred degrees centigrade. Its upper useful temperature is limited by the ability of its components to withstand high temperatures, its heaters' ability to heat it to a high temperature, and the uniformity of heating of the emissive material which can be achieved. One can speculate that uniformity of heating might be improved by designing a larger, deeper box for better air circulation, by strategically locating more heating elements and circulating fans, and by finding a different material emissive at millimeter wavelengths but having greater thermal conductivity. A very limited number of possible emissive materials were tested in this study. However, the design data and experience gained so far is sufficient to permit the design of a calibrator if needed for future investigations.

V. OPEN RESONATOR STRUCTURES

A. Fabry-Perot Optical Interferometer

The Fabry-Perot interferometer, as first designed more than 60 years ago,[22] consisted of two accurately plane mirrors spaced from a few millimeters to a few centimeters apart and maintained quite precisely parallel to one nother. If the mirrors have a reflectance of about 80 percent and a separation of one centimeter, the circular interference fringes[23] formed with light of wavelength 5×10^{-5} cm are sharp enough to permit a chromatic resolving power of 3×10^{5}; that is, distinguishably separate sets of fringes are formed for wavelength differences as small as 0.02 Ångstrom unit (1 Å = 10^{-8}cm). The Fabry-Perot interferometer (with adjustable separation) and the Fabry-Perot etalon (fixed spacing) have found considerable use in the investigation of the hyperfine structure of lines in optical spectra and in the work of Benoit, Fabry, and Perot[24] on the comparison between optical and mechanical standards of length.

It is a matter of some difficulty to adjust the silvered plane surfaces of the Fabry-Perot plates so that they closely approach exact parallelism. The use of spherically curved reflectors greatly eases this orientation problem and at the same time (for a fixed resolving power) yields a higher intensity in the transmitted fringes. This new form of optical interferometer was introduced by Connes[25] in 1956. Early forms of the ruby laser utilized polished planar end faces as had been

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(22) Ann. Chimie Physique, Vol. 22, p. 564; 1901.

(23) F.A. Jenkins and H.E. White, "Fundamentals of Optics," Third Edition, McGraw-Hill Book Compnay, Inc., New York, N.Y., pp. 274-283; 1957.

(24) Benoit, Fabry, and Perot, Trav. et Mem. Bur. Int. des Poids et Mesures, Vol. 15; 1913.

(25) P. Connes, "Enhancement of the product of luminosity by resolution of an interferometer using a path difference independent of incidence," Revue d'Optique, Vol. 35, pp. 37-42; 1956.

suggested by Schawlow and Townes;[26] recent lasers, including gas lasers for CW operation, most frequently make use of concave spherical reflectors.

B. Fabry-Perot Microwave Interferometer

Besides the optical uses just cited, the Fabry-Perot interferometer has for some time found application as a resonant structure for microwave and millimeter wavelength radiation. In 1953, Artman[27] used a Fabry-Perot instrument at 6 mm wavelength, and Culshaw[28] performed measurements at 35 Gc using a pair of plane reflectors each consisting of a set of spaced quarter-wave sheets of dielectric. In a later series of articles[29][30][31][32] Culshaw treats quite extensively the millimeter wave Fabry-Perot interferometer. The confocal resonator, which utilizes two identical spherical reflectors separated by a distance equal to their common radius of curvature, has been analyzed theoretically by Boyd and Gordon.[33]

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(26) A.L. Schawlow and C.H. Townes, "Infrared and optical masers," Phys. Rev., Vol. 112, p. 1940; 1958.

(27) J.O. Artman, "A microwave Fabry-Perot interferometer," Rev. sci. Instrum., Vol. 24, p. 873; 1953.

(28) W. Culshaw, "The Fabry-Perot interferometer at millimetre wavelengths," Proc. phys. Soc., B. Vol. 66, p. 597; 1953.

(29) W. Culshaw, "Reflectors for a microwave Fabry-Perot interferometer," IRE Trans on Microwave Theory and Techniques, Vol. MTT-7, pp. 221-228; April, 1959.

(30) W. Culshaw, "High-Resolution millimeter wave Fabry-Perot interferometer," IRE Trans on Microwave Theory and Techniques, Vol. MTT-8, pp. 182-189; March, 1960.

(31) W. Culshaw, "Resonators for millimeter and submillimeter wavelengths," IRE Trans on Microwave Theory and Techniques, Vol. MTT-9, pp. 135-144; March, 1961.

(32) W. Culshaw, "Further considerations on Fabry-Perot type resonators," IRE Trans on Microwave Theory and Techniques, Vol. MTT-10, pp. 331-339; September, 1962.

(33) G.D. Boyd and J.P. Gordon, "Confocal multimode resonator for millimeter through optical wavelength masers," Bell Syst. Tech. J. Vol. XL, pp. 489-508; March, 1961.

At the Research Division of ECI, investigation of open resonator techniques in the millimeter wavelength range has been continuing under an Air Force contract[34] for about a year. This work has included the construction and testing of half-confocal resonators, some study of coupling methods, and the measurement of Q-values. The half-confocal resonator, a modification of the confocal geometry, consists of one reflector with a concave spherical surface and one plane reflector. When the two reflectors are separated by a distance equal to half the radius of curvature of the spherical surface, the electrical (and optical) image of the concave surface is situated at that same distance behind the plane reflector. The spherical reflector and its image thus constitute a confocal Fabry-Perot resonator of convenient form. At a frequency of 35 Gc (wavelength 8.6 mm), using brass mirrors 15 cm in diameter, values of Q up to 66,000 were obtained. Coupling into and out of the resonator was accomplished with thin irises at the mirror surfaces. Insertion losses as low as 13 db were measured. Figures 11 and 12, taken from a progress report[35] on the Air Force contract mentioned above, show the variation of Q and insertion loss, respectively, with mirror separation. Six distinguishable types of TEM modes were observed; the highest values of Q are associated with the lowest order mode.

The ready accessibility of regions of high field strength in open resonators suggests the use within them of devices and structures which are difficult or impossible to incorporate in conventional waveguide, particularly at higher frequencies. Diodes operating as detectors or harmonic generators may be used within open resonators. It may be feasible to achieve efficient coupling to other non-linear materials such

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(34) Contract AF 19(628)-397 with Air Force Cambridge Research Laboratories.

(35) J.W. Dozier, M.J. King, F. Sobel, "Research for Open Resonators, Diode-Array Harmonic Generators, and Optical Beam Steering," Electronic Communications, Inc., Quarterly Report No. 4 on Contract No. AF 19(628)-397; 1 January 1963 - 31 March 1963.

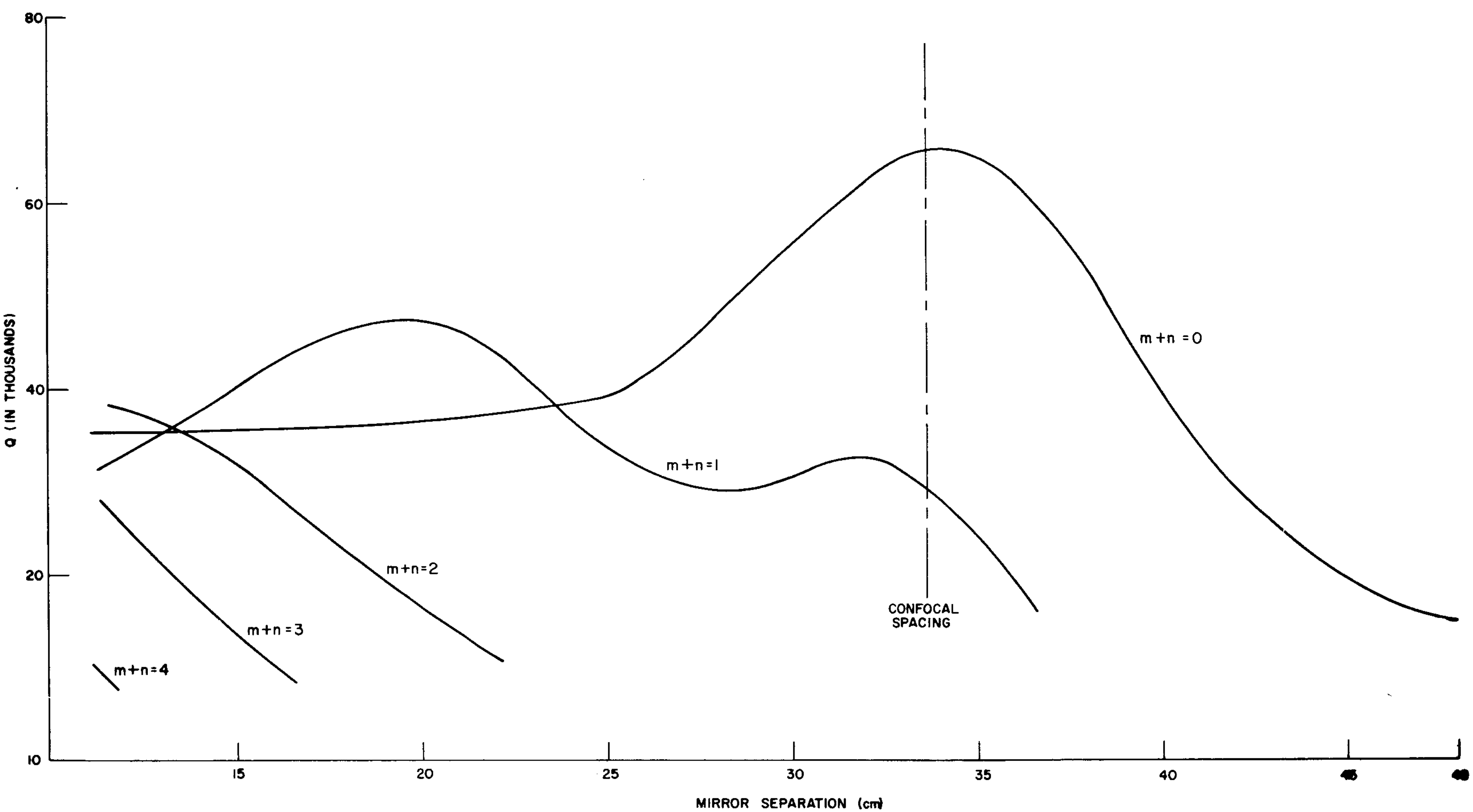

Figure 11 - Resonator Q vs Mirror Separation

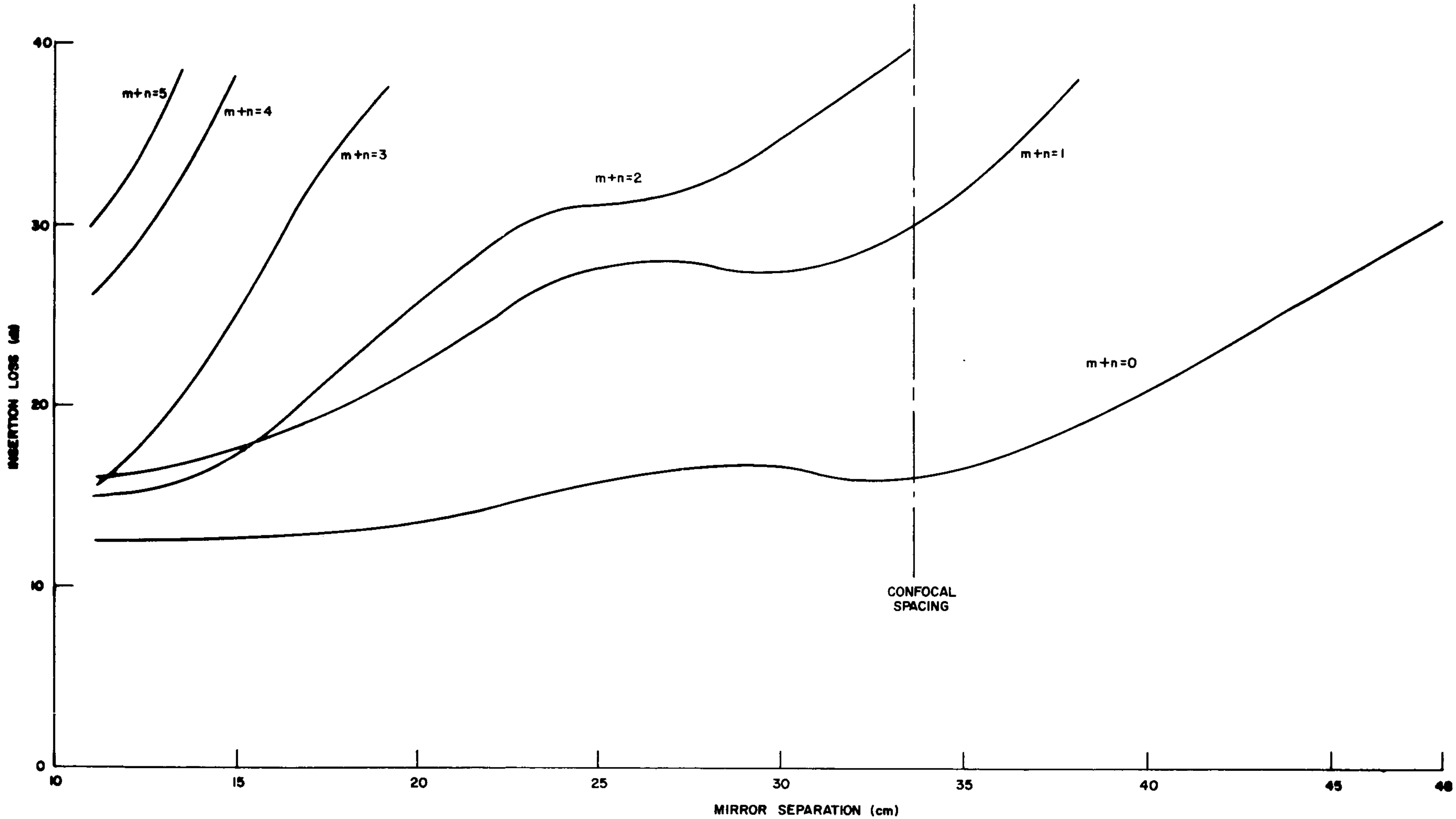

Figure 12 - Resonator Insertion Loss vs Mirror Separation

as ferrites, ferroelectrics or bulk semiconductors within resonant Fabry-Perot structures.

VI. FERROELECTRIC BOLOMETER

A. Background and Purpose

A number of millimeter wavelength measurements, e.g., harmonic generation efficiency and crystal conversion loss (both conventional mixing and harmonic mixing), are hindered by the lack of equipment to make low-level absolute power measurements at the shorter millimeter wavelengths. As a result, it is difficult to predict accurately the sensitivity of superheterodyne receivers and Dicke-type radiometers.

The method which is presently used to obtain a rough measure of the power level relies on the assumption that the sensitivity of a crystal video detector is the same at the shorter millimeter wavelengths as it is at a lower frequency where it can be measured. This assumption is known to be inaccurate, but it is still used for lack of a satisfactory alternative. It is known that the direction of the error is such as to yield a low reading of the millimeter wavelength power. The above error in turn results in pessimistic measurements of harmonic generation efficiency and optimistic measurements of mixer crystal conversion loss.

In view of the necessity for accurate power measuring instrumentation in order to perform other tasks of this program, experiments have been conducted to demonstrate the feasibility of using a ferroelectric bolometer for measuring millimeter wavelength power.

B. Theory of Operation

The operation of the ferroelectric bolometer depends on producing a large change in the dielectric constant of a ferroelectric material with a small change of temperature. The small temperature change in turn results from the absorption of millimeter wavelength energy. The ferroelectric bolometer takes advantage of what normally are limitations in the use of ferroelectric materials. These usually undesirable properties are: (1) high sensitivity of dielectric constant to temperature and, (2) increasing dielectric loss tangent with increasing frequency. Due to the latter effect, the ferroelectric material should be characterized by a high absorptivity at the shorter millimeter wavelengths. The absorption could be measured as a change in capacity due to dielectric constant change. At audio frequencies ferroelectric materials have relatively high Q's (50 - 300) and therefore low loss. Hence, audio frequency power may be used to measure the capacity change without contributing to it.

A device similar to that described above has been proposed as a sensitive detector of modulated infrared radiation.[36] The primary objective of our investigation is to develop a device for the measurement of absolute power levels.

The dielectric constant of a ferroelectric material is very temperature sensitive near its Curie temperature. The Curie temperature of a ceramic ferroelectric depends upon its constituents. A mixture of 35% lead titanate ($PbTiO_3$) and 65% strontium titanate ($SrTiO_3$) was chosen for the first ferroelectric to be used in this investigation. The mixture is referred to in mole percent. It was selected because its Curie point is near room temperature. Measurements by Sharpe and Brockus[37] at 3.0 Gc indicated a Curie temperature of about 28°C.

C. Application to Absolute Power Measurement

There are two possible methods for utilizing the ferroelectric capacitor as an absolute power measuring device at short millimeter wavelengths. One is to measure the capacity change with a capacity bridge and to determine the unknown power with the aid of a calibration of capacity change versus RF power at a lower frequency. The second method is to use a bridge circuit which balances RF power at millimeter wavelengths against RF power at some lower frequency where the power

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(36) R.A. Hanel, "Dielectric bolometer: a new type of thermal radiation detector," J. opt. Soc. Amer., Vol. 51, pp. 220-224; February, 1961.

(37) C.B. Sharpe and C.G. Brockus, "Investigation of Microwave Properties of Ferroelectric Materials," The University of Michigan, Final Report on Contract DA 36-039-sc-75003; March, 1959.

is measurable by other devices such as calorimeters. Both methods assume that the capacity change as a function of RF power is independent of frequency over a range from some frequency where power can be measured by other methods, to the higher frequency at which power measurements are desired. If the capacity change is not frequency independent, but some trend in the variation with frequency can be found, then the technique may still be useful at a short millimeter wavelengths by extrapolating the results from the shortest wavelength at which the ferroelectric bolometer can be calibrated.

The measurements of capacity change made in this study have been made by a capacitance substitution method using a reference capacitor and a capacitance bridge. The smallest capacity change which can be read on the reference capacitor being used is 0.1 picofarad. However, the bridge will unbalance with smaller changes and therefore is sensitive to smaller amounts of RF power. The smaller RF power could be measured with a better reference capacitor.

D. General Description of Bolometer and Design Considerations

The bolometers studied on this contract have all been in the form of small cylinders. The circular faces have been metallized and leads attached to them to form a capacitor. Various means of forming the capacitor plates and connecting the leads have been tried. In each case the capacitor was mounted centrally in a hollow rectangular waveguide with the axis of the cylinder perpendicular to the broad walls of the waveguide. An adjustable short was used in the waveguide behind the bolometer to maximize the energy absorbed by the ferroelectric.

Various considerations governed the design of the capacitor and its leads. It had to fit in RG-99/U waveguide where most of the testing was to be done. It was desirable that it also fit in RG-138/U, the next smaller waveguide, for comparative tests at higher frequencies. The pellet should be shaped for maximum capacity. It should absorb most of the power from the incident RF wave. The leads were made to support the capacitor at the center of the waveguide. The leads should conduct a minimum of heat away from the pellet but should make good electrical contact at audio frequencies. The difficulty of assembling such a small part and the necessity of working under a microscope had to be considered.

E. Objectives of Experimental Program

The first objective was simply to determine if the predicted effect of capacity change due to RF power absorption would occur and be of a magnitude to be observable for the ferroelectric composition and size of pellet chosen. The effect was observed with the first model.

The next objectives were to improve the bolometer mechanically and electrically. A series of changes were made in seeking a method of forming metal plates on opposite ends of the pellet and a method of attaching leads securely to the capacitor so formed. It was a goal to assemble a bolometer which could be transferred from one waveguide to another and back again without its coming apart. Another objective was to improve the sensitivity of the bolometer, that is, to obtain greater capacity change per unit applied RF power. Considerable effort was made to understand the fectors affecting the sensitivity since, at one stage of the investigation, results were poor and earlier data could not be reproduced. The problems were resolved, however, and the last model was of rugged construction and had a sensitivity 25 times that of the first.

The fourth objective was to determine the frequency dependence of the bolometer calibration. The use of a ferroelectric bolometer as an absolute power meter at frequencies where other devices are not available depends upon a knowledge of its response as a function of frequency. This would be measured by comparison with Wollaston wire bolometers or water calorimeters over a range of frequencies including the highest frequency at which such devices can be used. Comparisons over a 12% frequency band in one size waveguide were made as a start toward the fourth objective.

F. Test Methods

The first test performed on each bolometer was to measure its "activity" as a function of temperature. The bolometer was mounted in a section of RG-99/U waveguide. An electrical resistance heating coil was placed around the waveguide. A thermocouple was mounted inside the waveguide wall near the bolometer. The ferroelectric capacitor's leads were connected to a capacitance bridge, General Radio model 650 A, which was driven by a 1000 cycle generator. The calibrated capacitor in a Q meter, Boonton model 190-A, was used instead of the capacitor in the 650A. Cans of chilled refrigerant were placed about the mount under a cover to cool the device to about 15°C for the beginning of a test run. Through the use of the heating coil, the temperature was increased and the capacity measured at many intervals. Measurements were continued until the capacity had decreased to its initial value after the Curie point of the ferroelectric material was reached. Figure 13 is the graph of a typical set of data. Note that it was the capacity of the bolometer, mount, and leads which was measured. The slope of the plotted data was a measure of the capacity change or "activity" of the ferroelectric.

The usual procedure was to measure the capacity as the temperature was increased since this was more convenient. One bolometer was tested during both increasing and decreasing temperature. The typical hysteresis effect of the ferroelectric was observed.

From the plotted data of the first test a temperature was selected for which the slope of the capacity curve was steep. This temperature was used as the operating point for the second test: a measurement of capacity change as a function of millimeter wave power. An E-H tuner provided an impedance match at the RF input to the bolometer mount. A calibrated attenuator was used to vary the RF power level. An absolute reference was established with a thermistor. Raytheon type QKK 369 and QKK 866 and Amperex type DX-151 klystrons were the sources (at different times) of test frequencies from 64 to 78 Gc.

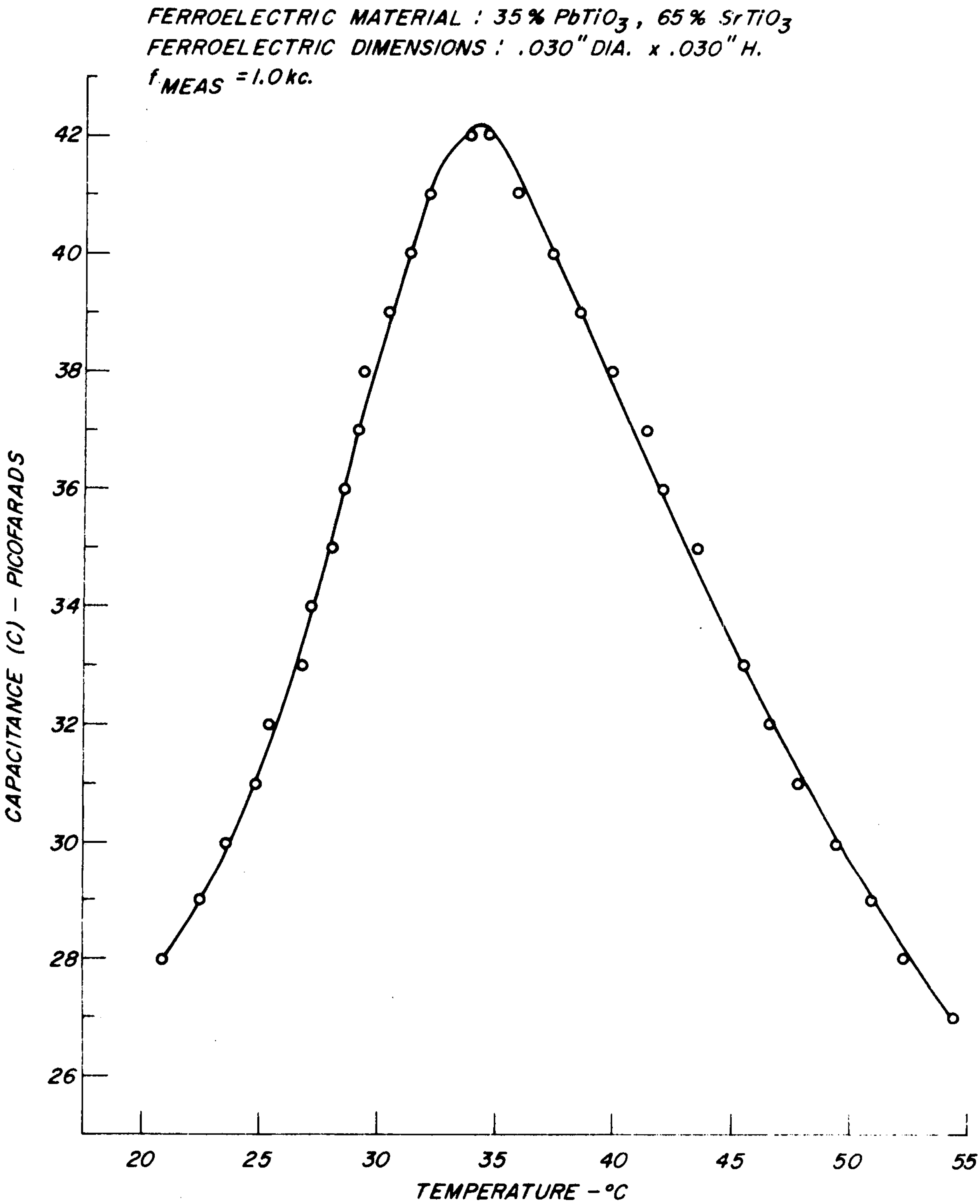

FIG. 13 – CAPACITANCE vs TEMPERATURE FOR THE FIRST BOLOMETER

G. Specific Bolometers and Test Results

Figure 14 is a drawing of the first ferroelectric bolometer to be constructed and tested during these investigations. The structure consists of a small cylinder (0.030" high x 0.030" diameter) of ferroelectric material mounted in RG-99/U waveguide. Gold electrodes were formed by brushing Du Pont no. 6976 gold paste on the planar faces and then baking at 760°C for about one hour. The posts which support and contact the ferroelectric disk are ceramic rods which have been completely coated with gold in the same manner. The thin gold coating on the ceramic rods provides a high conductivity path for the audio and millimeter wavelength currents and a low thermal conductivity path for the heat generated within the ferroelectric. Considerable difficulty was encountered in making a good solder connection between the circular faces of the gold-coated ferroelectric disk and the coatings on the two ceramic rods. The disk was soldered to the lower post only, while a pressure contact was used with the upper post. The lower post is in electrical contact with the waveguide. The upper post is insulated by plastic tape as it passes through the upper waveguide wall.

Tests of this bolometer were successful in that application of millimeter wave power to the mount did cause a capacity change as measured with an audio bridge. The test data are plotted in Figure 15. A test was made at each of seven different ambient temperatures. The capacity increased at the three lower temperatures and decreased at the four higher temperatures. This reversal of effect occurred between 26.7° and 29.6°C and verifies the expected reversal at the Curie temperature of 28°C for this particular ferroelectric material. The capacitance values of Figure 15 include the capacity of the test leads. For use as a bolometer, it is desirable to operate at the ambient temperature at which the capacity is changing most rapidly. The greatest change measured with this first bolometer was 2 picofarads with 40 milliwatts of 70.2 gigacycle power applied at an ambient temperature of 23.9° centigrade.

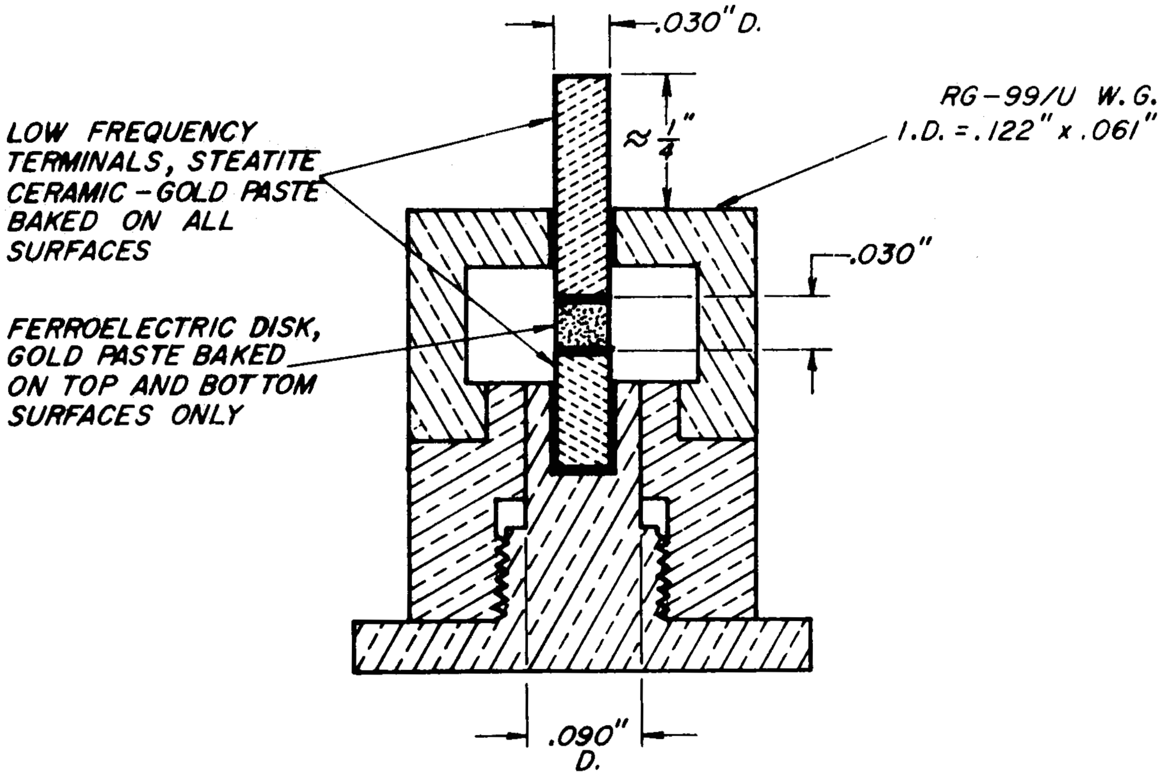

FIG. 14 - FIRST MODEL OF FERROELECTRIC BOLOMETER

FERROELECTRIC MATERIAL : 35% $PbTiO_3$, 65% $SrTiO_3$
FERROELECTRIC DIMENSIONS : .030" DIA. x .030" H.
f_{RF} = 70.2 Gc
$f_{MEAS.}$ = 1.0 kc

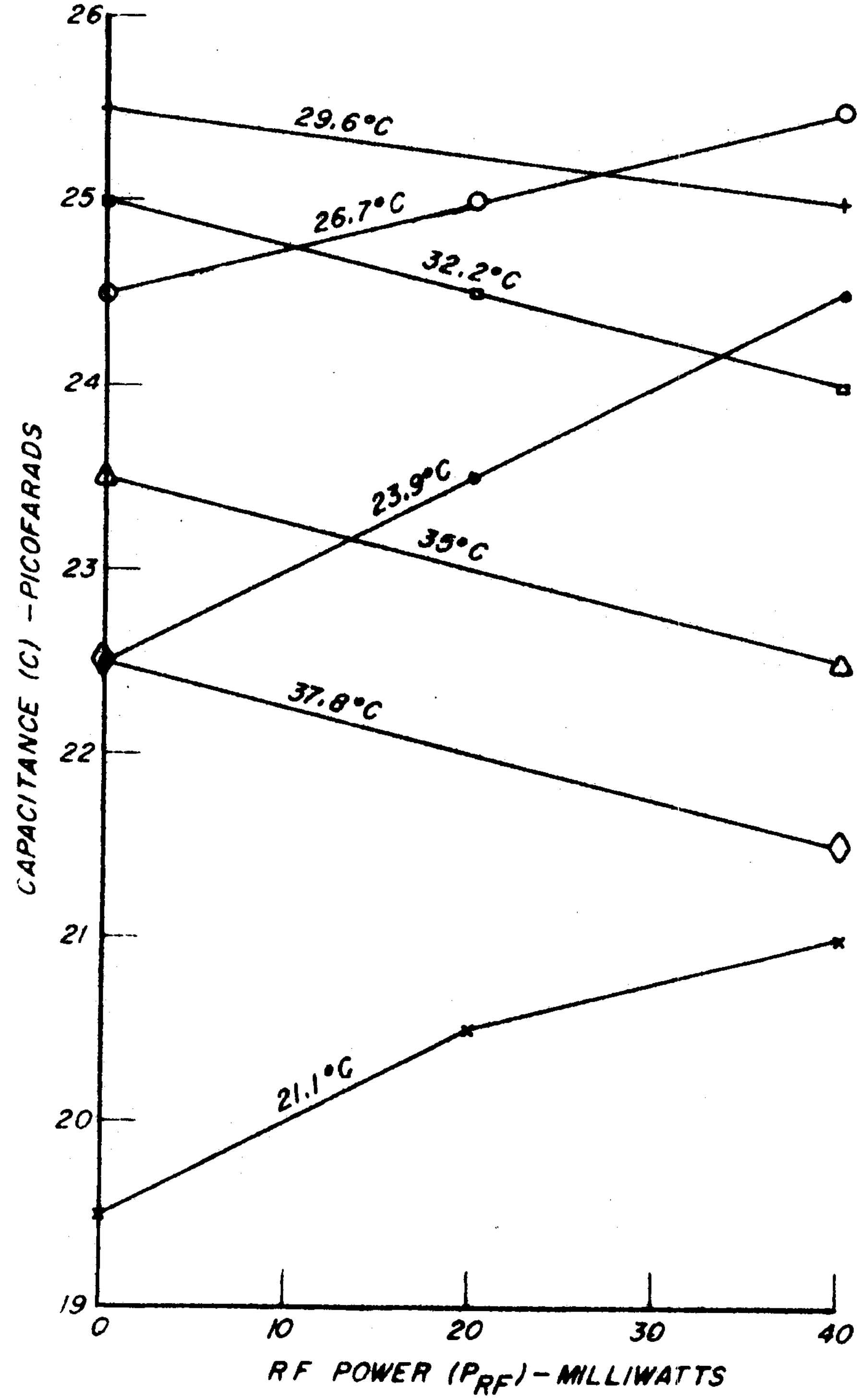

FIG. 15 – CAPACITANCE vs RF POWER AT VARIOUS TEMPERATURES – FIRST FERROELECTRIC BOLOMETER

After verification of the occurrence of the desired phenomenon described above with the first bolometer, efforts were concentrated on redesigning the ferroelectric pellet to obtain greater capacity change for a given amount of applied RF power. A more sensitive bolometer was needed to achieve the goal of measuring the small power output of harmonic generators at millimeter wavelengths. A pellet was cut 0.0205" high by 0.0205" diameter, a reduction in volume of 68%. It was reasoned that absorption of the same amount of RF power by a smaller volume should raise the temperature more and result in a greater capacity change. At the same time other changes to the bolometer design were tried in an attempt to make better contact with the pellet. Metal foil disks were cemented to the circular faces of the pellet with gold paste. Copper foil failed because it oxidized during the curing of the paste at 760°C. A bolometer with silver disks gave very low capacity change as a function of temperature, possibly because the silver migrated into and contaminated the ferroelectric. Other investigators have previously found that silver readily penetrates into ceramic materials under the influence of either elevated temperatures or high electric fields.[38] Finally, gold foil 5 mils thick was used and a capacity change of 2.5 pf was measured for 30 mw of 70 Gc power at 24°C ambient. This was a slight improvement over the first bolometer.

The gold-coated ceramic posts remained an unsatisfactory means of making contact with the pellet inside the waveguide. They were suspected of absorbing a portion of the RF energy. A bolometer was assembled using copper wires (AWG #40, 3.1 mil diameter) instead. These wires extended axially from the cylindrical pellet, as did the ceramic posts, and were soldered to the gold foil disks. Measurements of this unit showed about the same capacity change as before.

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(38) I.E. Balygin and K.S. Porovskii, "Effects of electrode metal on insulation aging of ceramic dielectrics," Sov. Phys. - Tech. Phys., Vol. 2, p. 459; 1957.

Another approach was tried to increase the capacity change in the next bolometer constructed, namely reducing the pellet thickness insofar as possible and increasing the capacitor plate area without increasing the volume excessively. This next pellet and all those fabricated since have been 0.010" thick and 0.040" diameter. This thickness is about the minimum to which the ferroelectric material can be worked. The first pellet made in this size was designated bolometer A. Its capacity changed 3 pf when tested at 22.5°C with 20 mw of power. This result was measured at three frequencies -- 69, 72, and 78 Gc. See Figure 16. The design changes incorporated in bolometer A resulted in its having three times the capacity change measured for the first ferroelectric bolometer.

An attempt was made with bolometer A to achieve the fourth goal of the experimental program, that is, to determine the frequency dependence of the bolometer's response. Measurements of capacity change in RG-99/U at 69, 72 and 78 Gc (12% band) were in good agreement. The pellet was then transferred to RG-96/U waveguide in order that it might be tested at 35 Gc. A wire and a gold disk came off during the transfer and had to be resoldered. In RG-99/U waveguide, the activity of bolometer A had measured 2.7 pf change per degree C. In RG-96/U waveguide, it now measured 1.2 pf change per degree C. It was suspected that the bolometer's characteristics might have changed when it was repaired. The bolometer was returned to RG-99/U guide for retest before proceeding. It then gave even poorer results, measuring 0.6 pf change per degree C. Also, 20 mw of power at 70 Gc gave only 0.3 pf change, one-tenth the sensitivity previously measured. The attempt to achieve the fourth goal ended until the reasons for the very poor sensitivity could be found and a stronger mechanical design could be developed.

There followed an extended period of experimentation in which various mounting arrangements were tried. Solder and flux for attaching the leads were eliminated by cutting flat leads integral with

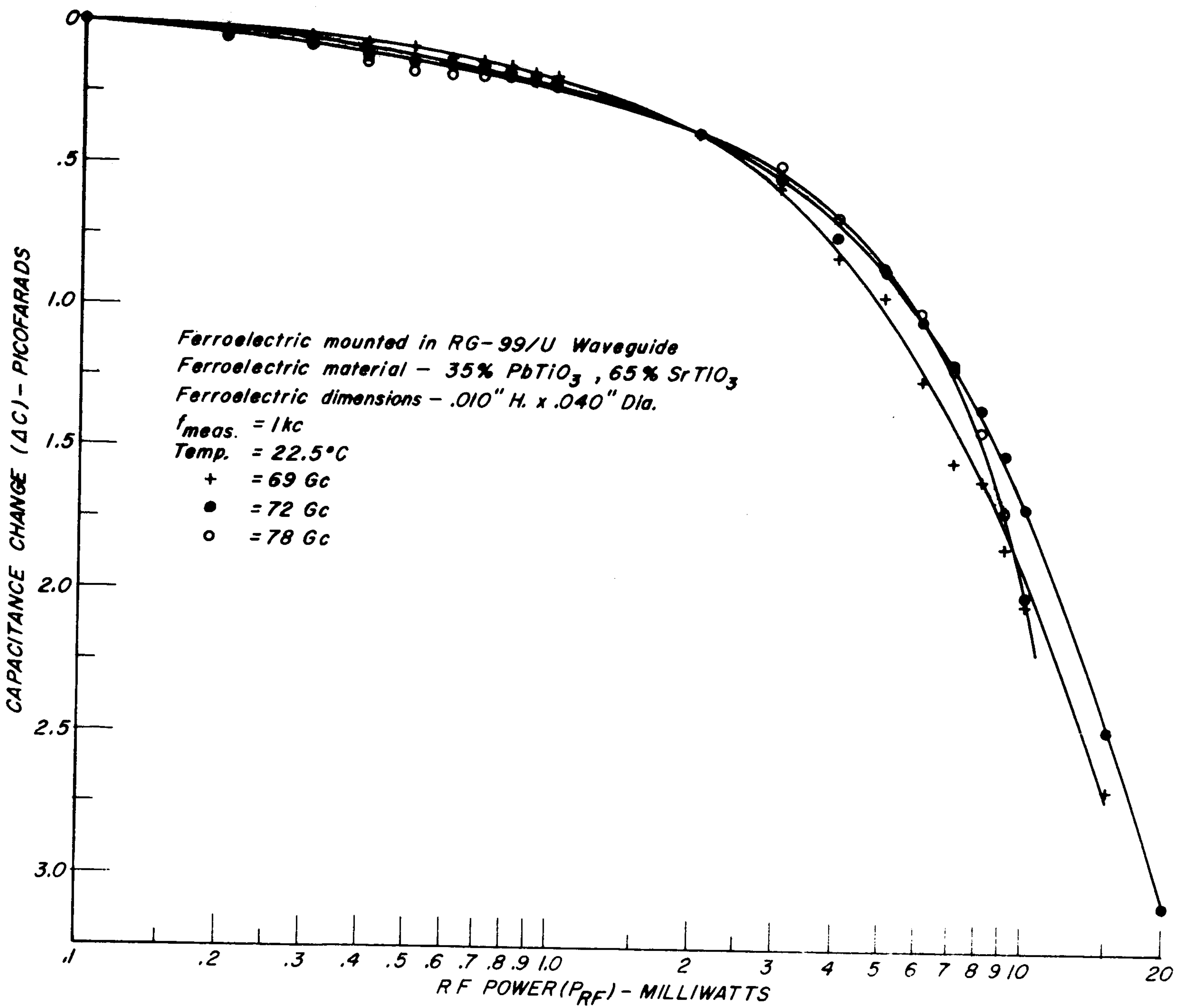

FIG. 16 - RESPONSE OF BOLOMETER A AT THREE FREQUENCIES

the gold foil capacitor disks. These were first bent up and brought out axially with respect to the cylindrical pellet. Later the waveguide mount was modified and the leads brought out raidally from the pellet through the sides of the waveguide. A microphotograph of this bolometer B is shown in Figure 17. The gold foil leads did not have the strength to support the pellet in the precise position desired and were replaced in bolometer C with 3 mil diameter wires of 90% platinum - 10% ruthenium. Instead of gold foil, gold paste only was used for both the capacitor plates and for attaching the wires. A microphotograph of a pellet with radial wire leads is shown in Figure 18.

The characteristics of bolometer C were measured and found to be superior to the previous bolometers. It was noted however, that its power sensitivity ($\Delta C/\Delta P$) was substantially reduced after it had been subjected to a moist atmosphere for long periods of time. If the bolometer was baked for a short period of time in order to drive out the absorbed moisture, the original performance was restored. This is illustrated in Figure 19.

The final effort during this contract was to assemble and test a second bolometer in the same configuration as bolometer C. The ferroelectric disc was fabricated at the same time and from the same bar of material as was used for bolometer C. Designated bolometer D, its properties were measured in the same manner as bolometer C. The measured capacitance versus temperature and capacitance change versus RF power level characteristics are shown in Figures 20 and 19 respectively. The salient characteristics of bolometers C and D are listed below for comparison.

	Curie Temp. (T_c)	Temp. Sensitivity for $T > T_c$ ($\Delta C/\Delta T$)	Power Sensitivity $T = 34^\circ C$ ($\lvert\Delta C/\Delta P\rvert$)
Bolometer C	$22^\circ C$	-1.2 pf/$^\circ$C	0.6 pf/mw
Bolometer D	27°	-2.5	1.27

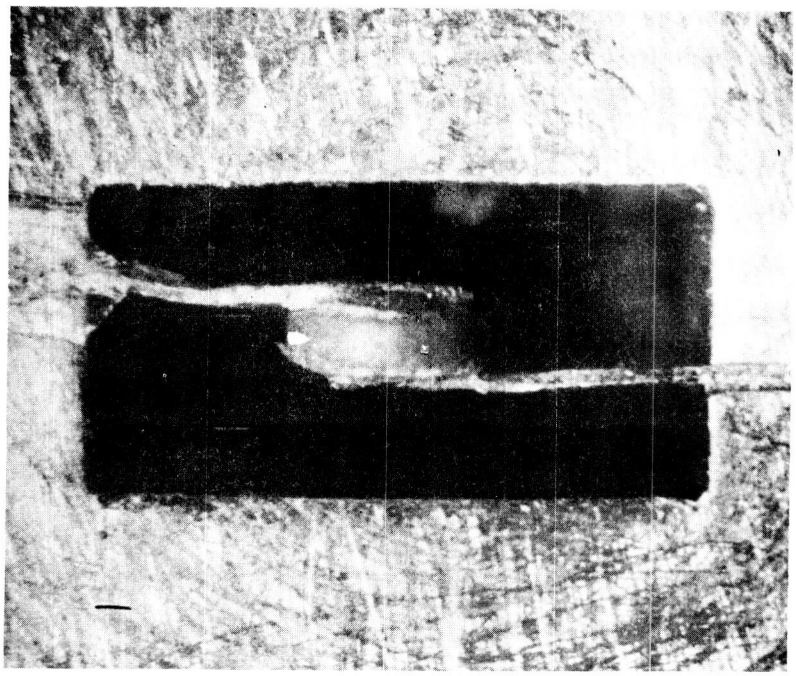

Figure 17 - Ferroelectric Bolometer Across Waveguide .122" x .061" I.D.

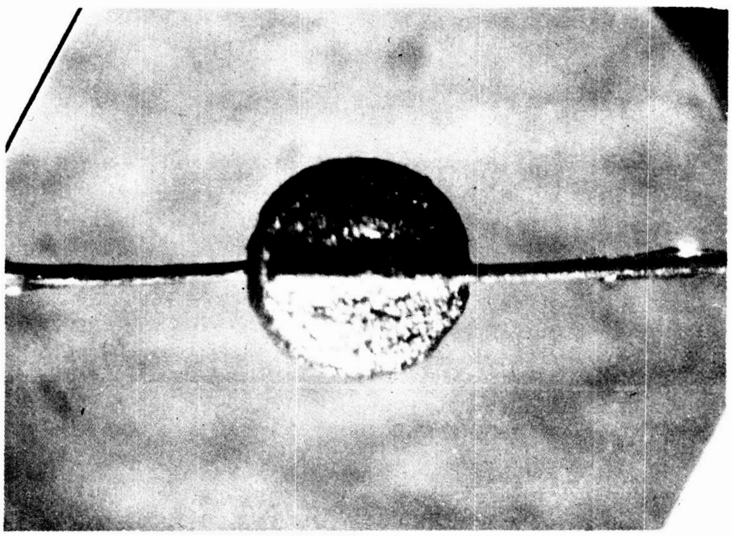

Figure 18 - Ferroelectric Bolometer with Radial Wire Leads

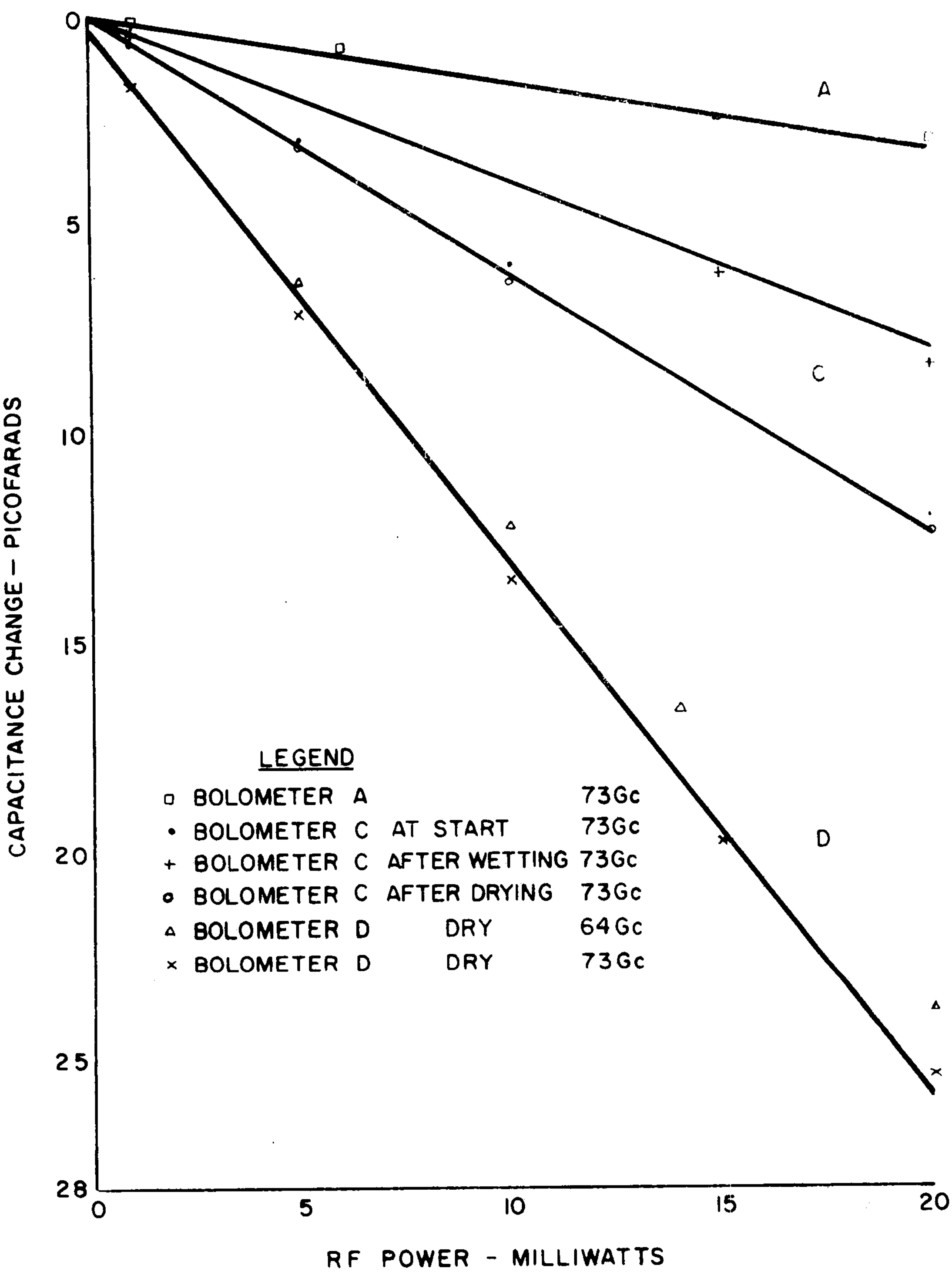

FIG.19 – RESPONSE OF FERROELECTRIC BOLOMETERS

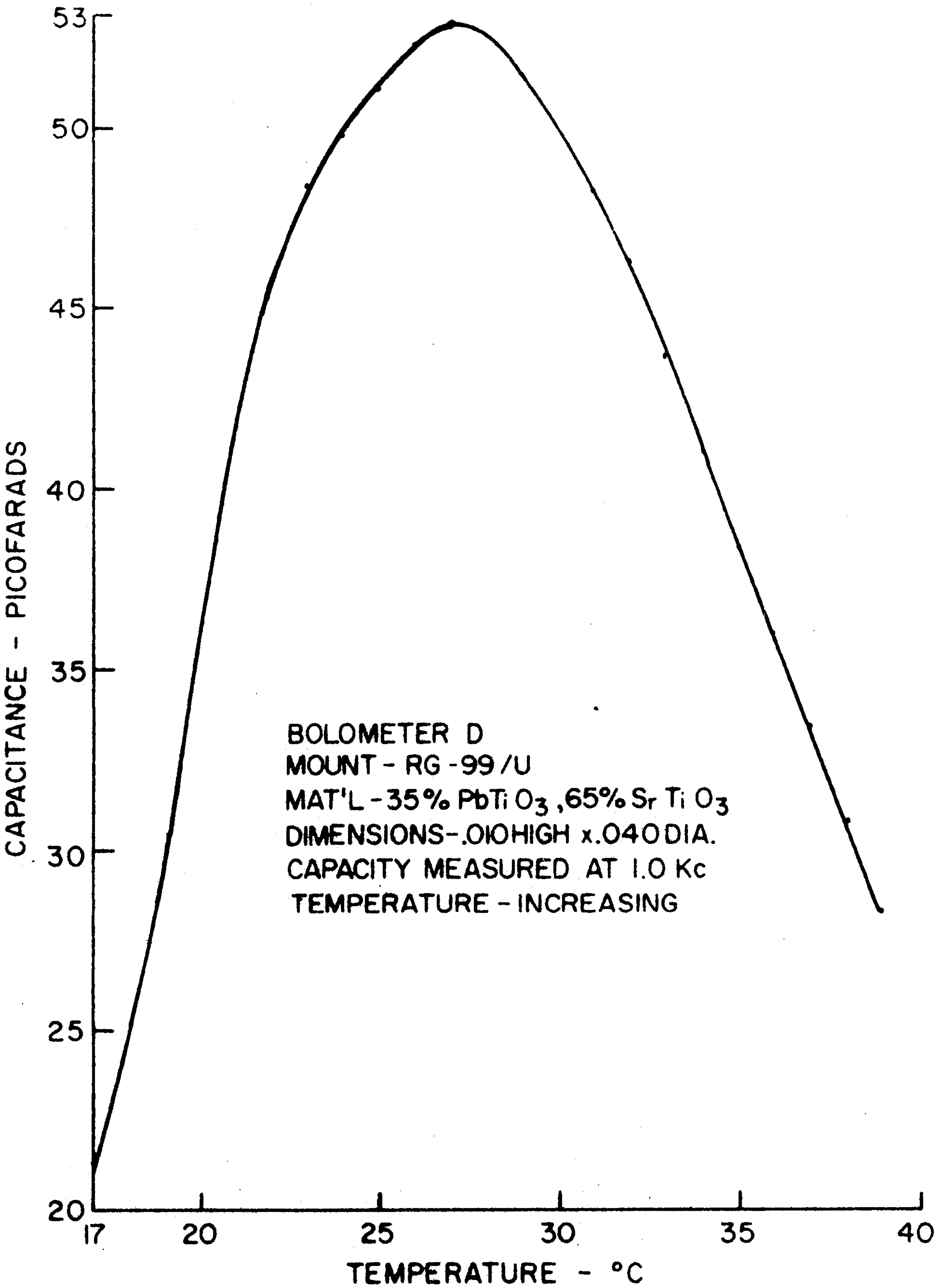

FIG. 20 - CAPACITANCE vs TEMPERATURE FOR BOLOMETER D

The anomaly of supposedly identical bolometers having such different characteristics is unexplained. The different indicated Curie temperatures imply there is some difference in the ferroelectric. Possibly the ceramic ferroelectric stock from which the 0.010" x 0.040" dia. discs were fabricated was not sufficiently homogeneous in density or ratio of constituents. Alternatively, there may still be significant unknown effects introduced during the fabrication process. Since both $\Delta C/\Delta T$ and $\Delta C/\Delta P$ for bolometer D were about double the values obtained with bolometer C, it is believed that the test procedures were accurate.

The data of Figure 19 for bolometer D, like that for bolometer C, show that the measured capacitance change is a linear function of the absorbed RF power. As a result, calibration curves can be obtained by measurements at only a few power levels. These few measurements can be made at relatively high power levels (> 1 milliwatt) where they can be compared with alternate absolute power measuring instruments such as a calorimeter.

A goal of the ferroelectric bolometer development has been to determine if the power sensitivity ($\Delta C/\Delta P$) of a given bolometer is independent of frequency. Some evidence of this is seen in the data for bolometer D in Figure 19. Measurements will have to be made over a much wider frequency interval to establish frequency independence.

H. Recommendation

It is recommended that a material with a high Curie temperature be investigated for the ferroelectric bolometer application. The use of a higher Curie temperature ferroelectric material offers a number of potential advantages as listed below.

1. The effect of ambient temperature variations is expected to be less of a problem with a bolometer maintained at an elevated temperature.
2. The absorption of moisture by the ferroelectric pellet is less likely at an elevated temperature.

3. It will be possible to operate on the low temperature side of the Curie temperature where $\Delta C/\Delta T$ (activity) is usually a maximum.

4. Since the dielectric loss tangent of ferroelectric materials is usually greater below the Curie temperature, it is expected that it will be easier to design a waveguide mount in which nearly all of the incident millimeter wave energy is absorbed by the ferroelectric pellet.

VII. ANTENNA STUDIES

A. Characteristics of Ideal Radiometer Antennas

The ideal radiometer antenna would receive energy only in the solid angle subtended by the body of interest. Real antennas receive signals from objects lying within a solid angle bounded by the major lobe or main beam of the antenna pattern and from all other directions in space occupied by sidelobes. The practical problems then are to design a radiometer antenna having sidelobes very much lower than the main beam and having a main beam of small enough solid angle to subtend only the object being measured. To the extent that this is not achieved, the radiometer measurement is affected by energy from other objects about the antenna.

B. Radiometer Antenna Applications

The requirement for the angular width of the main beam of radiometer antenna varies with the application. The extremes of beam-width requirements are represented by an instrument for measurements of remote heavenly bodies and by an instrument for measurements of the same bodies from planetary probes passing at short ranges. Different beamwidth requirements are met by varying the size of the antenna aperture. Broad beamwidths of tens of degrees may be achieved readily with small horn antennas at millimeter wavelengths. Narrow beamwidths of a fraction of a degree require large apertures. These may be achieved by use of focusing techniques akin to those of optical physics. Surface wave and leaky wave antennas also may be designed for narrow beamwidths.

Focusing may be accomplished by means of shaped reflectors or with refractive lenses. Both single parabolic reflector antennas[39] and double reflector types[40] such as Cassegrain systems are used.

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(39) H. Jasik, "Antenna Engineering Handbook," McGraw-Hill Book Co., Inc., New York, N.Y., p. 12-4 to 12-13; 1961.

(40) P.W. Hanna, "Microwave antennas derived from the Cassegrain telescope," IRE Trans. On Antennas and Propagation, Vol. AP-9, pp. 140-153; March, 1961.

Lenses are made of suitable low-loss dielectric and may conveniently be plano-convex[41] or flat Fresnel zone plates.[42] Comparisons between these different types are given in Table 1. The particular type chosen for a given application would depend upon the detailed requirements.

Lens antennas have been designed at ECI for several radiometers operating at millimeter wavelengths. The design has proven very satisfactory in field tests. The lens was mounted at the end of a tunnel lined with microwave absorber. A mechanical chopper was built in the tunnel at the other end next to the feed horn. The general arrangement is shown in Figure 21. If the lens dielectric loss is low, a thicker lens and shorter tunnel may be used. The first antenna tested had a Fresnel zone plate instead of a plano-convex lens. However, the detection of small reflectors in field tests was poor until the zone plate was replaced with a plano-convex lens. The probable reason for this is discussed in the following paragraph.

As mentioned at the beginning of this section it is insufficient that the main beam of the radiometer antenna subtend the target since energy is also received through sidelobes which, in practice, always exist. For ideal antennas, the percentage of power in the main beam remains constant as the aperture becomes larger. Since the same power occupies less and less solid angle, the ratio of the peak of the main beam to the average level of power in the sidelobes must increase. For narrow beam antennas this ratio becomes very large as is seen from the data in Table 2. If a particular antenna has sidelobes with an average level above the levels stated it means that a greater proportion of energy is being received in the sidelobes. Thus it is believed that the poorer performance of the Fresnel zone plate was due primarily to higher sidelobes caused by the step approximation nature of the zone plate.

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(41) S.A. Schelkunoff and H.T. Friis, "Antenna Theory and Practice," John Wiley and Sons, Inc., New York, N.Y., p 573-575; 1952.

(42) F. Sobel, "Fresnel zone plates for millimeter waves," Electronic Design (Microwaves), Vol. 10, pp. 20-27; March 15, 1962.

Property	Antenna Type			
	Reflector		Lens	
	Single	Double	Planoconvex	Fresnel zone plate
Curved Surface	Paraboloid	Paraboloid and Hyperboloid	Hyperboloidal or Spherical	None
Differences in Construction	Feed support	Subreflector support	Tunnel housing	Tunnel housing
Typical shape	Diameter > depth	Diameter > depth	Length > diameter	Length > diameter
Loss of RF line to feed	Appreciable	Negligible	Negligible	Negligible
Antenna loss	Negligible	Negligible	Dependent upon dielectric loss tangent	Minimal
Aperture blocking	Yes	Yes	No	No
Factors affecting amplitude taper	Feed pattern f/D	Feed pattern subreflector f/D	Feed pattern dielectric loss f/D	Feed pattern f/D
Sidelobes	Nominal	Nominal	Low	Higher
Backlobe	A problem	Low	Low	Low
Suitability for mechanical chopping	Poor	Good	Good	Good
Frequency bandwidth	Broad	Broad	Broad	Narrow
Other comparisons	May use offset feed for reduced aperture blocking	Most complex to align	May be made of quartz for sub-millimeter use	Lighter than planoconvex lens

TABLE 1. Outline Comparison of Properties of Large Aperture Antennas

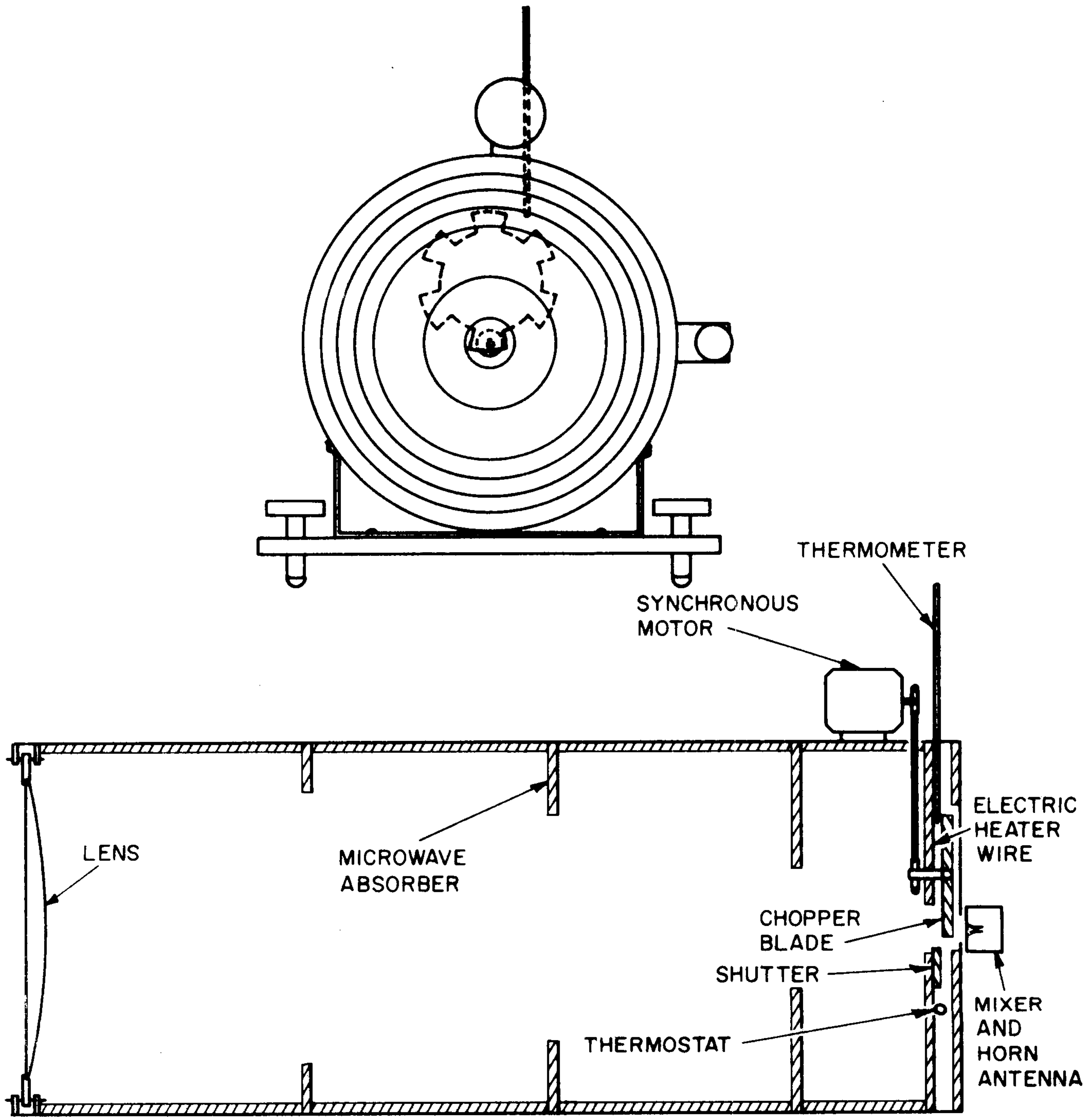

FIG. 21 - ANTENNA HOUSING, INTERNAL VIEWS

Aperture Diameter	Beamwidth (3 db)	Average Sidelobe Level	Outermost Sidelobe Level
wavelengths	degrees	decibels	decibels
29.5	2	40.7	61.9
59	1	46.5	70.9
118	0.5	52.7	80
236	0.25	58.7	89
472	0.125	64.7	98

TABLE 2. Data for Circular Apertures Uniformly Illuminated

A few comments on the data of Table 2 may clarify this problem. The data were calculated for a circular aperture with uniform illumination. For such an aperture, 47.6% of the total energy received is that received within the 3 db contour of the main beam.[(43)(44)] Table 2 was constructed by finding the ratio of the average energy per unit solid angle in the main beam to that in the sidelobes. For small beams the ratio increases 6 db each time the beamwidth is halved. Note that this number is an average and the actual sidelobes will differ from it. The first sidelobe of any uniformly illuminated circular aperture is down 17.6 db. Therefore the far out sidelobes of a large aperture must be very low. The theoretical level of the last real sidelobe for each different aperture is given in Table 2. In practice the aperture illumination is tapered and the sidelobes should be even lower.

It is usually impossible to measure accurately the antenna pattern in the region of such low sidelobes because of the lack of sensitivity and dynamic range in available instrumentation. Therefore it was

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(43) "Antenna Studies of Focused Apertures in the Fresnel Region," Electronic Communications, Inc., ASTIA Document 291 764; June 1, 1962.

(44) M. Born and E. Wolf, "Principles of Optics," Pergamon Press, New York, N.Y., p. 397; 1959.

impossible to compare measured radiation patterns of the Fresnel zone plate and the plano-convex lens. The better performance of the radiometer with the plano-convex lens implies that it had lower sidelobes. The sidelobes of the zone plate are low by normal standards but in radiometer applications seem to contribute an intolerable amount. If the average sidelobe level increases 10 db, the energy received within the 3 db contour of the main beam drops to 9% of the total received.

Another type of antenna which is stepped is the stepped parabolic reflector described by Richter.(45) The steps are $\lambda/25$ or less with the result that sidelobe level and gain are not noticeably affected. The purpose of stepping the reflector is to defocus any light or infrared energy to avoid heating the feed. This could be a serious problem in space use where the sun's rays are not attenuated by an atmosphere.

C. Arrays of Discrete Antenna Elements

Mention should be made of work in applying antenna array techniques to millimeter wavelengths. A major problem in designing discrete arrays for narrow beamwidths is the feed network for many elements. An approach to this problem is being studied at Electronic Communications, Inc., under a contract with the U.S. Army Electronic Research and Development Laboratory. Progress reports are available as issued from ASTIA.(46) The method is to excite an array of slots cut in the side of a trough waveguide which is propagating a single surface-waveguide mode. The properties of the trough and coupling slots are being studied. Patterns of simple arrays are being plotted. In the future the application of this work will permit construction of thin antennas with various beam positions.

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(45) E.W. Richter, "Stepped microwave antenna," Microwave J., Vol. 5, pp. 95-97; May, 1962.

(46) M. Cohn and R.S. Littlepage, "Investigation of Improved Airborne Antenna Techniques for Combat Surveillance," First Quarterly Progress Report on Contract DA-36-039sc-90750, Electronic Communications, Inc., ASTIA Document 290 347; September 30, 1962.

VIII. SUMMARY

Investigations of a number of techniques applicable to millimeter wave superheterodyne receivers have been described. Such receivers, as diagrammed in Figure 22, may be used in place of video receivers for increased sensitibity in radiometric measurements. Studies performed on the contract have given data applicable to the design of antenna, modulator, and mixer. Work has also been done on thermal calibrator and millimeter wave bolometer designs since these devices are needed in the development and evaluation of millimeter radiometers.

The development of a ferroelectric bolometer, further study of ferrite modulators, and experimentation with point-contact diodes as harmonic generators and mixers is being continued at ECI under Contract NASw-662. On the program reported herein the feasibility of the ferroelectric bolometer was proven and approaches to a number of design problems were explored. A ferrite modulator utilizing the principle of Faraday rotation was operated at 140 Gc but further effort is necessary to reduce the insertion loss over a broad bandwidth. Assembly techniques for point-contact diodes were devised and preparations made for an experiment to evaluate a variety of whisker and crystal materials. Equipment was assembled for measuring the performance of harmonic mixers having broad microwave intermediate frequency bands.

Some of the design data developed on this contract has been used in the design of two radiometers.[47] These operated at 140 Gc and 225 Gc and achieved minimum detectable temperature differences of $0.3^{\circ}K$ and $1.0^{\circ}K$, respectively, when a 10 second integration time was used. Their detailed performance is given in Table 3. The measured performance of these radiometers demonstrates the feasibility and superiority for this application of harmonic-mixing, microwave IF, superheterodyne receivers at frequencies above 100 gigacylces.

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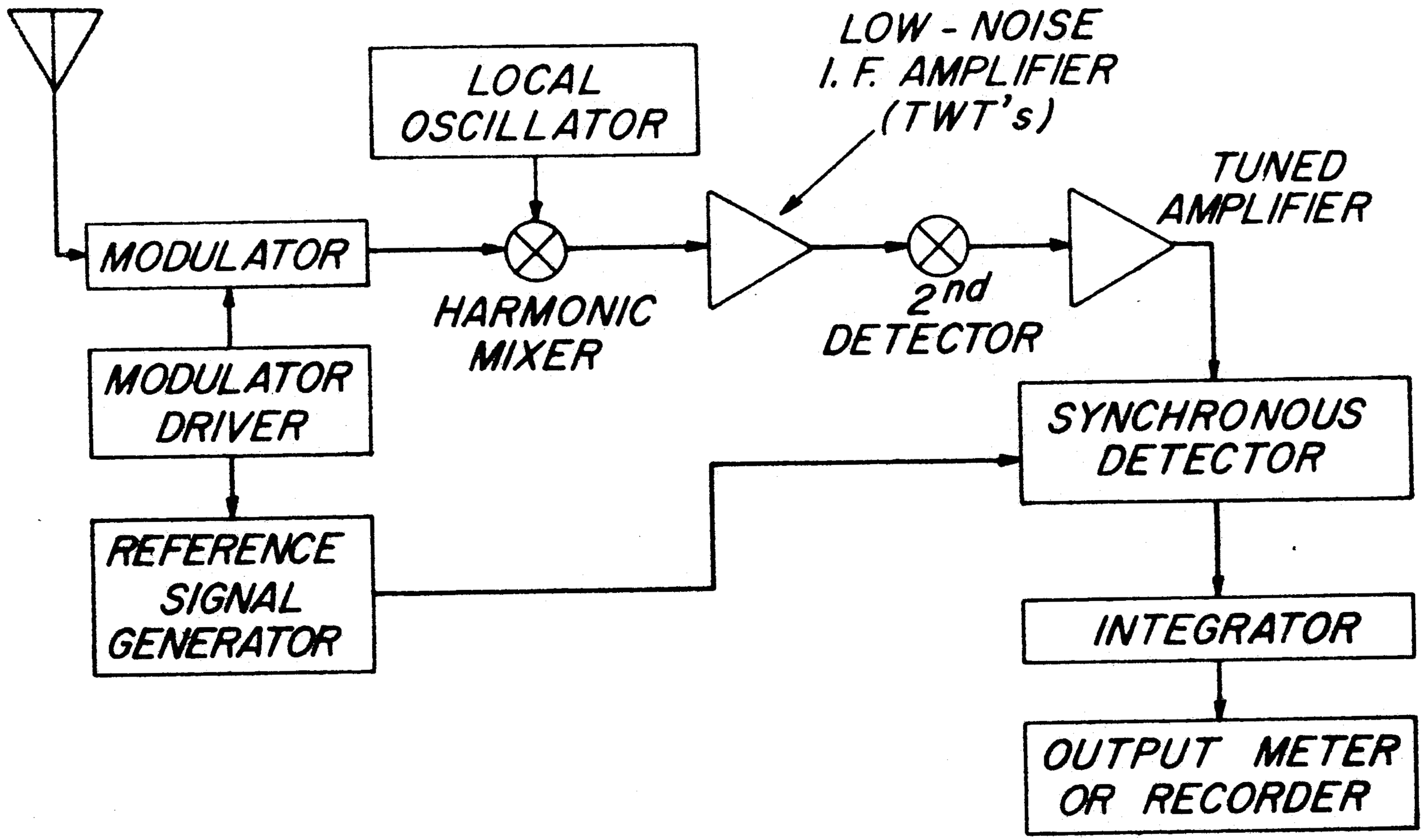
(47) See the reference in footnote number 7.



BLOCK DIAGRAM OF SUPERHETERODYNE RADIOMETER

FIG. 22

Radiometer frequency	140 Gc	225 Gc
Harmonic mixing number	2	3
Local oscillator frequency	70 Gc	75 Gc
IF noise figure	5 db	5 db
IF bandwidth	1.5 Gc	1.5 Gc
Integration time	10 sec	10 sec
Detected temperature difference (ΔT) for tangential signal ($S/N = 8.5$)	$2.6^{o}K$	$8.5^{o}K$
$(\Delta T)_{min}$ for $S/N = 1$, calculated	$0.3^{o}K$	$1.0^{o}K$
Radiometer noise figure, calculated	20 db	26 db
Crystal noise ratio	< 2.0	< 2.0
RF losses, estimated	2 db	3 db
Crystal conversion loss, calculated	15 db	20 db

TABLE 3 - Performance of Experimental Millimeter Radiometers

Figure 3 - Low Noise TWT

and Power Supply

REDUCE TO 7"

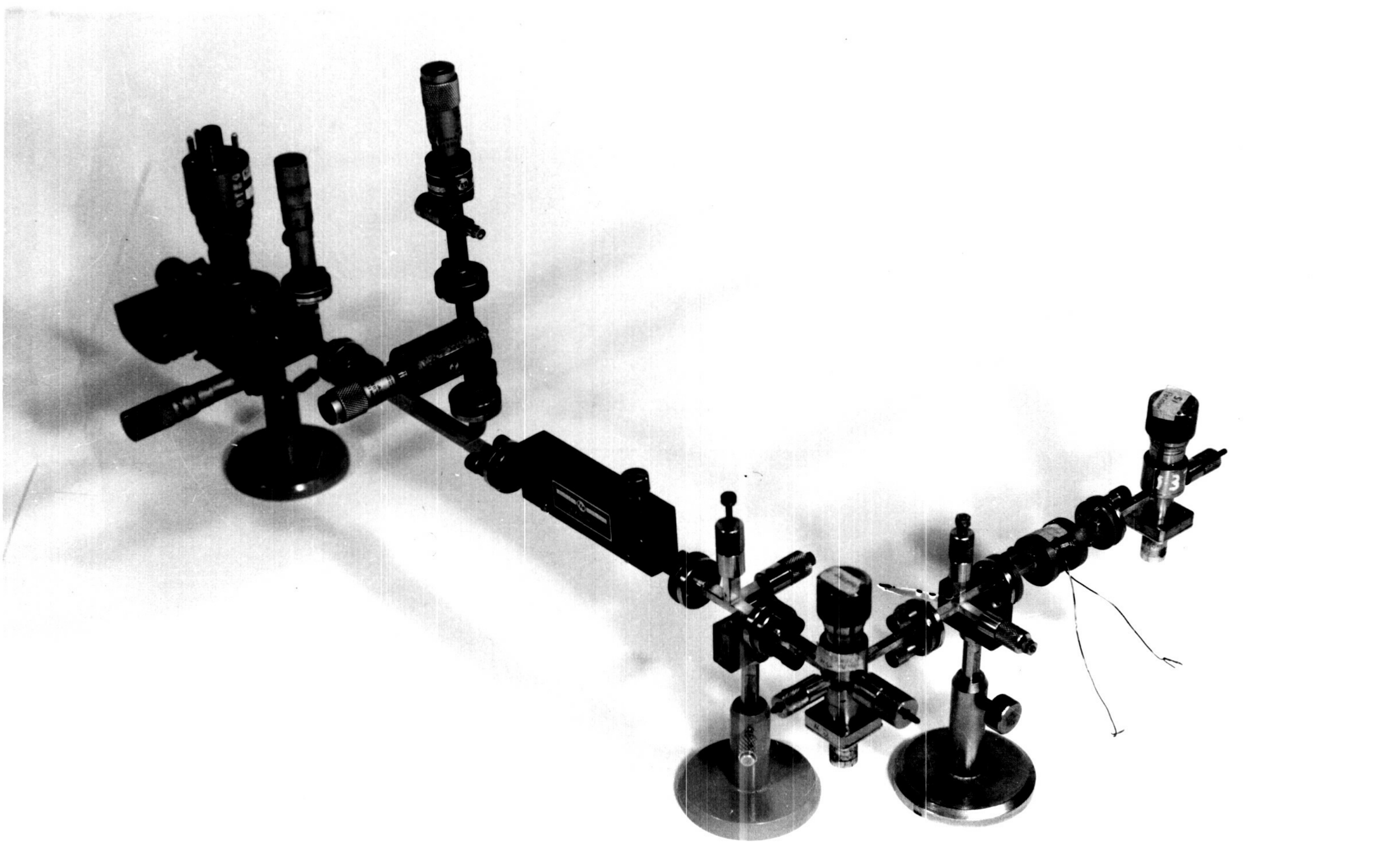


Figure 8 - Faraday Rotator

and Test Setup at 2 mm

REDUCE TO 7"

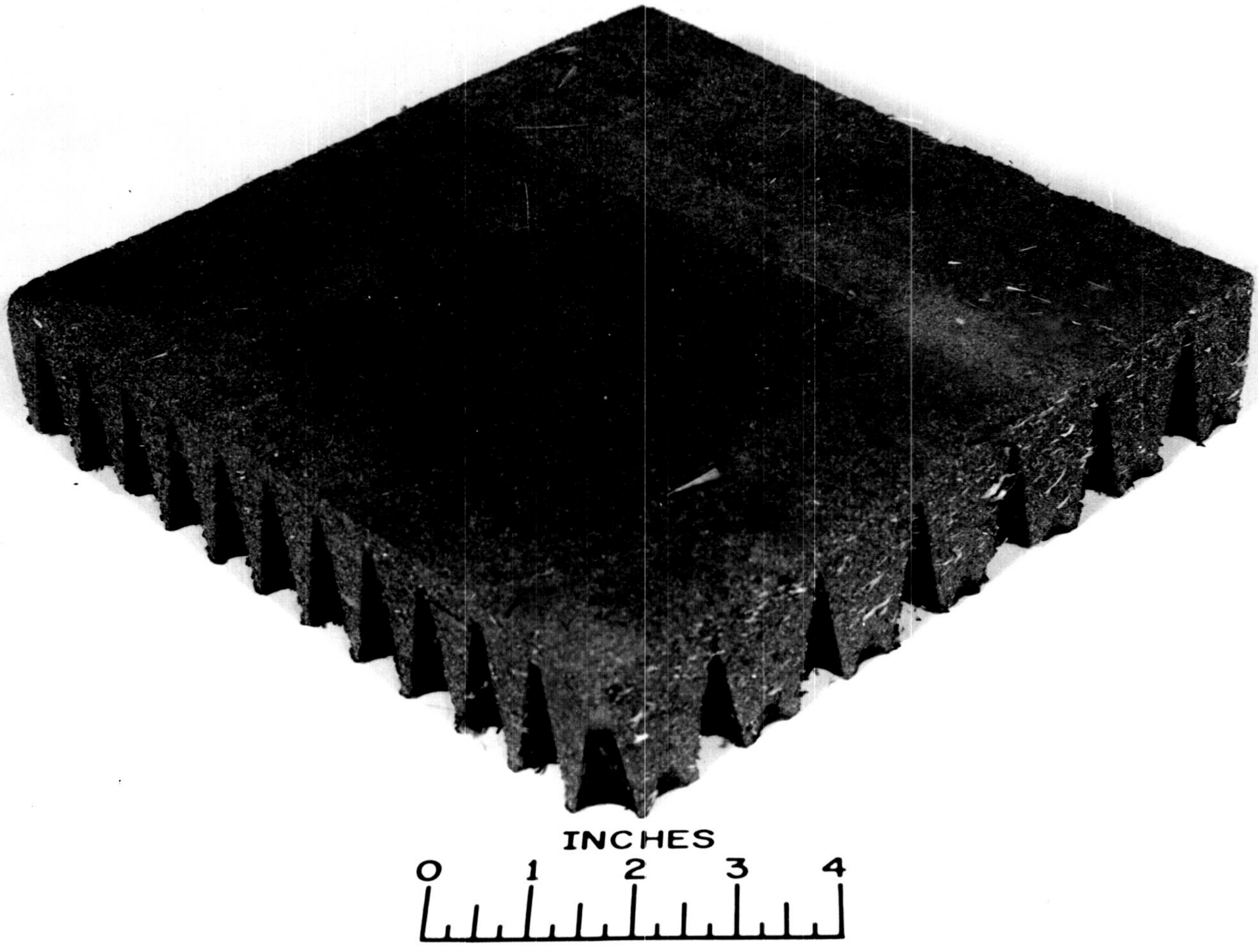


Figure 10 - Millimeter Wave
Absorber/Emitter

REDUCE TO 7"

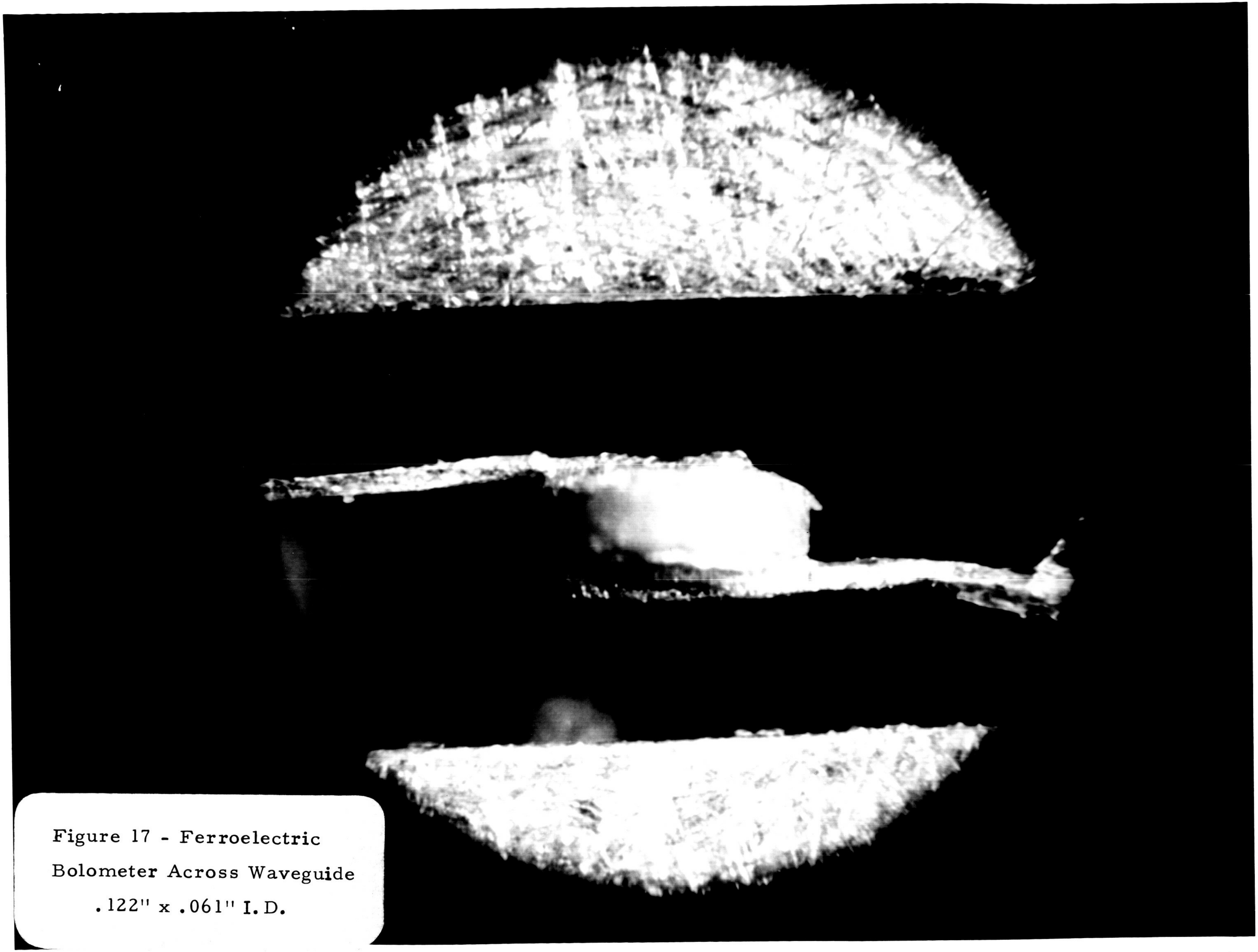


Figure 17 - Ferroelectric Bolometer Across Waveguide .122" x .061" I.D.

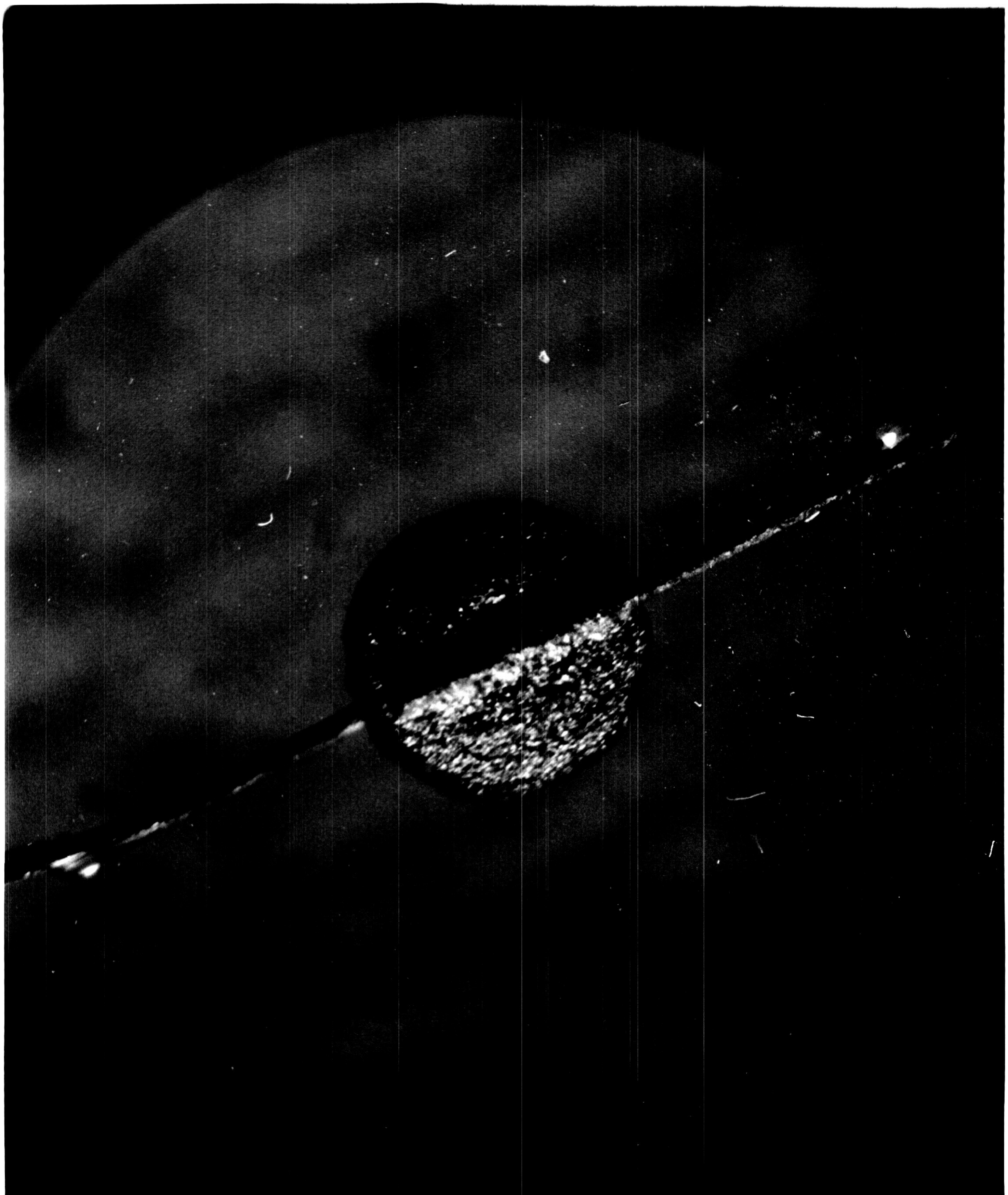


Figure 18 - Ferroelectric Bolometer with Radial Wire Leads